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REGULAR PAPER

Enhancing data delivery in vehicular networks using dual-radio architecture

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Abstract
Vehicular ad-hoc networks (VANETs) have drawn increasing attention from both academia and industry. With the proliferation of sensor and wireless technologies, a large amount of sensory data need to be transmitted among vehicles for various intelligent transportation applications such as autonomous vehicles. The conventional WiFi-based VANETs cannot perform well due to its short communication range. To this end, we introduce a hybrid dual-radio architecture consisting of a 2.4 GHz WiFi and a 433 MHz Eagle Eye (EE) radio characterized by long-range, low-rate, and low-cost communication. Through this EE radio, a mobile node can "see" more nodes in a farther distance to improve the quality of next relay selection for packet delivery using WiFi. Collaborating between WiFi and EE radios, we propose a novel dual-radio routing protocol that significantly alleviates the delivery delay in a distributed manner. To evaluate the performance, we build a dual-radio prototype to verify its feasibility and efficiency. Furthermore, extensive simulations conducted using 4000+ taxis' trajectories in Shanghai demonstrate that the proposed dual-radio architecture and protocol can reduce up to 50% delivery delay in VANETs.

Keywords Vehicular networks · Delivery delay · Dual-radio architecture

1 Introduction

Vehicular ad-hoc network (VANET) (Hartenstein and Laberteaux 2008) is one branch of mobile networks lacking continuous connectivity. Both industry and academia pay great attention to VANETs. For example, vehicles in urban can use WiFi/DSRC radio and ad-hoc pattern to form a vehicle-to-vehicle communication (Lin et al. 2017) for safety data sharing. Typical researches include multicasting in social VANETs (Gao et al. 2009), directional routing in green VANETs (Zeng et al. 2013), and geographic based vehicular routing (Soares et al. 2014).

One fundamental service provided by VANETs is data sharing (Xiang et al. 2015), in which one source node sends its data to a destination node through multi-hop and carry-and-forward delivery fashions. The amount of delivery data is exponentially increasing because of two reasons. On one hand, the scale of VANET becomes larger. For instance, the U.S. DOT has committed to the use of IEEE 802.11p wireless devices on new light-duty vehicles. Messages can be transmitted by most vehicles in near future. On the other hand, with the rapid growth of sensor and multimedia technologies, the size of data becomes larger. For instance, previous vehicles only share their speed and location information for safety. However, future vehicles would transmit more data for not only safety but also entertainment, social network, and crowdsensing (Wang et al. 2018).

A satisfactory data sharing service requires nodes to reliably transmit data even VANETs with intermittent connectivity, random mobility and limited sensing coverage. Therefore, VANETs are supposed to maximize the delivery ratio. However, the wireless channels in highly dynamic VANETs are not perfect, leading to erroneous data or data

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loss. That is to say, some data cannot reach the destination forever. Hence, according to (Jain et al. 2004), we select the average delivery delay as the principal metric to evaluate the efficiency of VANETs.

It is non-trivial to design a practical scheme to reduce the delivery delay dramatically in VANETs. Firstly, there is still no practical infrastructure in most recent VANETs. Thus, packets have to be opportunistically carried and forwarded to its destination by intermittently connected nodes. Its successful delivery is not severely guaranteed. Secondly, it is common that there are some collisions during wireless transmissions (Silva et al. 2015). A dynamic routing with collision avoidance mechanism is required to improve the efficiency and reliability. Thirdly, the communication range is limited. Through information exchange among neighbors, a vehicle can acquire the movement states of other nodes only within its communication range. However, most nodes seriously suffer from a short communication range. In conventional VANETs, the only radio takes in charge of both the information exchange and data delivery tasks. Plenty of approaches are studied to optimize the utilization of radio and select the optimal relay within communication range. But these approaches cannot break the bottleneck of the short range. Then, researchers resort to infrastructures to facilitate data passing. For example, extra stationary infostations are proposed in Throwboxes (Banerjee et al. 2010) and 5G mm wave is proposed to be used in VANET (Kong et al. 2017). However, infrastructure deployment in large-scale VANETs is hard and expensive.

Rather than designing efficient schemes based on existing VANET architecture, we introduce a hybrid dual-radio architecture, which adds an additional long-range low-rate Eagle Eye (EE) radio with negligible cost on current VANET nodes. By comparison, EE radio can cover as 10x range as WiFi. In our dual-radio architecture, the EE radio undertakes the information exchange, while the short-range high-rate WiFi radio is in charge of the data delivery.

The dual-radio architecture is composed of three main components—a GPS module, a WiFi module and a long-range transceiver (i.e., EE radio). The former two components have usually been equipped in existing VANET nodes, and the EE radio is the only new component added in our system. Using the GPS module, a movement information including location, velocity, direction, and time stamp can be generated and exchanged by EE radio. Leveraging this information, we propose a novel routing protocol specialized for dual-radio architecture. First, a utility function is designed to estimate the expected delivery delay of each node within the EE range. Then, the optimal next relay is selected by the minimal expected delivery delay and no collision from the EE range. Finally, the WiFi radio transmits the actual data to the selected relay with the collaboration of multi-hop neighbors. The advantages include: (1) Compared with the communication range of WiFi, EE radio has a longer range to collect the real-time movement information of more vehicles, which leads to a better next relay selection because of more knowledge and more accurate estimation. (2) Different tasks are assigned to different radios, in which the small-size movement information exchange is assigned to the low-rate EE radio and the large-amount data delivery is assigned to the high-rate WiFi radio. These two radios can work simultaneously because they operate at different bands: 433 MHz and 2.4 GHz. This parallel communications further save time for packet delivery.

In order to evaluate the performance enhancement, we build a VANET testbed using seven prototype nodes moving in campus scenario. Experimental results show the superiority of the dual-radio architecture and routing protocol in terms of delivery delay and delivery ratio. For further studying the performance in a large-scale scenario, extensive simulations are conducted using real traces 4000 taxis in Shanghai (Huang et al. 2007). Simulation results demonstrate that the dual-radio architecture reduces up to 40% delivery delay compared with the conventional WiFi-based VANETs.

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

- We propose a novel dual-radio architecture to enhance the delivery performance in VANETs, which consists of one short-range high-rate WiFi radio for data delivery and one long-range low rate EE radio for information exchange.
- We design a new dual-radio routing protocol tailored to our dual-radio architecture. This protocol leverages the long-range EE radio to collect the movement information of more nodes and select the optimal next relay, which has minimal delivery delay and low collision probability.
- We build the prototype of dual-radio architecture. In addition, we conduct extensive simulations to compare the performance of dual-radio routing with existing protocols.

2 Related work

In literature, two categories of efforts are close to our work: Classic taxonomy of VANET delivery and recent advances in VANET delivery.

2.1 Classic taxonomy of VANET delivery

In order to improve the performance of packet delivery, a variety of schemes have been proposed in VANETs.

In the spatial dimension, Jain et al. (2004) formulate the routing problem that packets are delivered end-to-end across a node graph with time-varying connectivity. They propose several schemes using global information about holistic networks. However, it is difficult to acquire global information in real VANETs. LTE could support global information but requires extra fees from drivers. Therefore, most existing schemes are based on local information, i.e., neighbors' movement information. Context-aware routing protocols (Musolesi and Mascolo 2009) and socially-selfish-based routing protocols (Li et al. 2011) are typical works in this field. In contrast, EE radio makes up the vacant space between local and global space owing to the long-range radio as illustrated in Fig. 1.

In the temporal dimension, historical traces based routing protocols (Jones et al. 2007; Xiao et al. 2013) have been widely investigated. These algorithms/protocols implicitly assume that the future traces are similar to the historical ones, e.g., a bus in the bus networks. This assumption cannot be always held in real networks. Nevertheless, our dual-radio architecture can be applied to general VANET scenario, which leverages both historical and real-time information obtained by EE radio.

In the knowledge dimension, the classic information includes node id, position, velocity, direction and time stamp. But whether the travelling destination of a node (dx, dy) is known involves in the disputes. DAER routing (Huang et al. 2007) considers that all nodes know the dynamic (dx, dy). The spray-and-wait protocol (Spyropoulos et al. 2005) adopts the last observed location instead of the real destination approximately. In this work, (dx, dy) is set as an optional information.

In the delivery pattern dimension, Zhang et al. (2007) propose a classic routing protocol using epidemic spread. This protocol provides the theoretically optimal performance when mobile nodes have infinite bandwidth and buffers. Then, Singh et al. (2013) extend the above work to multi-destination routing, and significantly narrow the forwarding node space from all to just a few nodes. However, limited by existing hardware, recent VANET nodes cannot support the

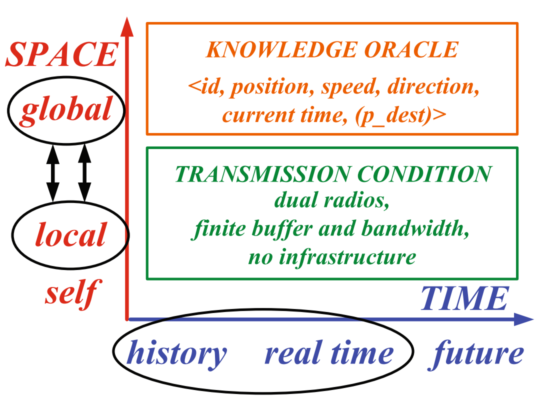


Fig. 1 The operating scope of EE radio in spatio-temporal dimension

infinite bandwidth and buffers. In our dual-radio architecture, we assign each node with finite bandwidth and buffers for practice.

In the infrastructure dimension, infrastructures are additional platforms that can receive, store and forward data packets. General infrastructures include smart phones (Talipov et al. 2013), access points (Banerjee et al. 2010), and roadside units. However, it is not cost-effective to deploy communication infrastructures. It is nor appropriate to dynamic VANETs where nodes are with high-level of mobility. Therefore, our scheme designs a plug-in module attached to mobile nodes that requires no communication infrastructure.

In the social dimension, recent works has been proved that social networks can further optimize the data delivery in VANETs (Abdelkader et al. 2013; Gao et al. 2013; Hui et al. 2011). These social attributes are orthogonal to our dual-radio architecture. Hence, they can work together to enhance the delivery performance.

2.2 Recent advances in VANET delivery

Besides the above dimensions, two kinds of studies are close to our dual-radio work. Network coding is one of the most popular research topics recently. In VANET field, there are also some works considering the network coding (Altman et al. 2013; Zeng et al. 2014; Zhang et al. 2013) to reduce the collisions in dense scenarios. As comparison, our dual-radio architecture improves the delivery performance from another perspective. In addition, network coding and dual-radio can also work together.

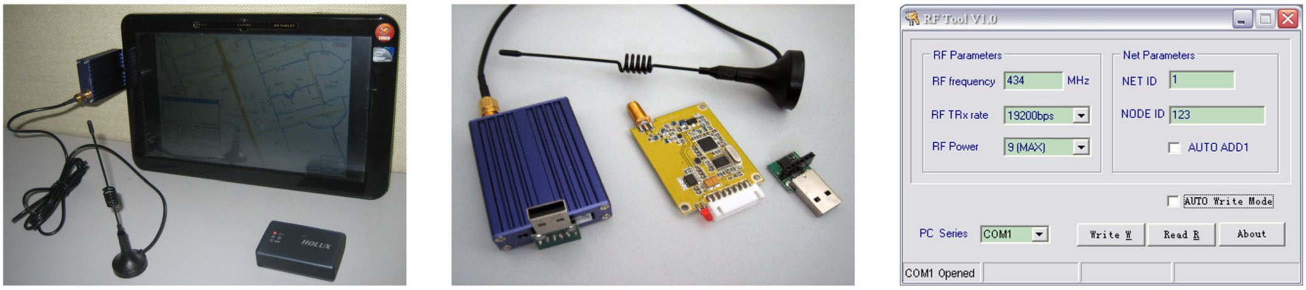
Dual-radio architecture has been investigated in several kinds of wireless networks (Dhananjay et al. 2009; Ji et al. 2011; Zhou et al. 2010; Polese et al. 2017). They use dual-radio nodes as stationary infrastructures and their two radios usually have the same communication range. In this work, we design a dual radio architecture for large-scale mobile VANETs, which is well-performed (performance shown in Sect. 6), yet inexpensive (the extra EE radio is less than 5 dollars) in real deployment. Furthermore, EE radio devices can cover longer-range area with a low data rate.

3 Design of dual-radio architecture

In this section, we introduce our dual-radio architecture. We firstly describe the hardware components and then present its communication features.

3.1 Dual-radio platform

Figure 2a illustrates the proposed dual-radio platform, involving three major modules: a HOLUX M-1000C GPS,



(a) The proposed dual-radio platform, including a PAD with WiFi, EE radio, and GPS

(b) The EE radio contains the transceiver chipset, which can connect PAD via USB

(c) The user interface of the development tool to initialize the EE radio

Fig. 2 The prototype of dual-radio platform

Table 1 Major parameters of the EE radio

Item	Configuration
RF rates	4.8, 9.6, 19.2 Kbps
RF freq.	418–445 Mhz (step 1 Khz)
TX power levels	0–9 (9 == 500 mW, 0 == 20 mW)
Built-in buffer	256 bytes
Size	50 mm ∗ 43 mm ∗ 14 mm
Operating temperature	− 40° to 85°
Sensitivity	− 119 dBm

Table 2 Basic configuration of the PAD

Item	Configuration
CPU	Intel atom-N270
FSB	667 MHz
Disk	500G SATA
Battery adapter	Input: 100-240 V, Output: 12 V 3 A
Screen	10.2 inch touch screen
Operating system	Ubuntu 14
Wireless card	Atheros AR9285
Wireless mode	IEEE 802.11a/b/g
Size	226 mm ∗ 167 mm ∗ 25 mm

a built-in AR9285 WiFi card in PAD, and an ADF7020 transceiver, i.e., EE radio. We connect all modules to a PAD. The EE radio connects PAD via USB and the GPS module communicates PAD using Bluetooth. Note that GPS and WiFi radio widely exist in recent mobile nodes, only the long-range and low-rate EE radio is a newly-added module, whose working band is 433 MHz and price is less than 5 dollar. In our design, EE radio collects real-time movement information of neighboring nodes. Since the size of movement information is no more than 300Bytes (Chen et al. 2016), EE radio works under CSMA/CA protocol. Figure 2b shows the EE radio box and built-in chipset. The transceiver's parameter is given in Table 1. The AR9285 WiFi card is a high-rate radio for short-range data packet delivery. To support VANETs, the WiFi radio works in ad-hoc mode and at IEEE 802.11b/g 2.4 GHz band.

The HOLUX M-1000C GPS module reports the real-time location once per second to the PAD and the localization error is at most 5 m regarding longitude and latitude. The system time is set to the GPS time so the platform clocks are synchronized. Table 2 lists the configurations of PAD. The computing capability is not strong, which indicates our design requires very low computational complexity. In addition, its built-in WiFi radio is qualified for operating the data delivery and processing experimental results. This PAD is a light-weight device so that it is convenient to be carried outside as a mobile node.

In the configuration part, we leverage Linux Wireless Extensions (LWE) to configure WiFi. To be specific, we can control the channel selection, transmission power and network id. For EE radio, we develop a dialog-based application for customization as shown in Fig. 2c. Users are able to tune the data rate, working frequency, and power level of EE radio. The SSCOM port is adopted to set these configurations for EE radio via serial port.

3.2 Preliminary comparison for communication ranges

The advantage of EE radio is to make use of its long-range communication capability to get more nodes' movement information in a larger area. To verify the range of EE radio, we carry out extensive outdoor experiments in campus scenarios and compare the rate-range relationship of WiFi radio and EE radio, respectively.

The average goodput between a transceiver and a receiver in different ranges is selected as the metric to evaluate the WiFi performance. The central frequency of the selected channel is 2.422 GHz, the bandwidth is 20 MHz, and the transmission power is 100mW. In the experiments, we record all real-time data rates in different ranges, where IEEE 802.11g supports 8 data rates: 6, 9, 12, 18, 24, 36, 48, 54 Mbps. We choose the lowest 6Mbps, the middle 24Mbps, and the highest 54Mbps to draw their average goodputs in Fig. 3a. From this figure, we observe that (i) The communication range is inversely proportional to the data rate; (ii) the upper bound of communication range is close to 200 m when the data rate is at the lowest 6Mbps.

Meanwhile, we are considering how far the EE radio can reach. To evaluate its performance, we conduct the outdoor experiments and measure the communication range as the distance from the source node to destination one. To be simple, we deploy the source node at a fixed position. This source node keeps sending "Hello" message. Through SSCOM, the data rate of EE radio could be controlled at 4.8, 9.6, and 19.2 Kbps. Then, the destination node keeps moving and listening. Once it cannot listen the Hello message, we log the distance and consider it as the maximum communication range. We test all three data rates and show the experimental results in Fig. 3b. From this figure, we observe that (i) EE radio can reach about 2500 m when its transmission power is 500 mw and data rate is 4.8 Kbps; (ii) The shortest communication range of EE radio is about 820 m when its power is only 20 mw and data rate is 19.2 kbps. This observation indicates a promising long-range feature of EE radio.

4 Dual-radio routing

To fully exploit the advantage of dual-radio architecture, in this section, we design the customized dual-radio routing for enhancing the data delivery in VANETs.

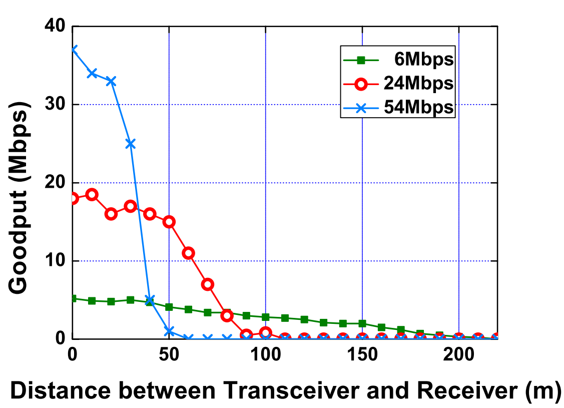
4.1 Problem statement

In our system, all vehicles, i.e., nodes, are equipped with the dual-radio platforms and move independently. The total number of nodes in the area of interests is n. Each node has a limited storage buffer and wireless bandwidth. One source node can delivery data to the destination in a either direct or intermediate manner. Any source node knows the ID of the destination node, but is not clear about its real-time location.

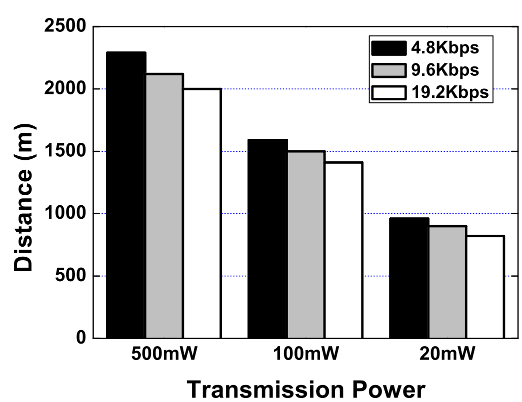
The data that need to be delivered by WiFi radio is much larger than the movement information. These data can be either the multimedia files, which are desired to share to friends as soon as possible, or the traffic environments, which need to broadcast to vicinities immediately for safety. The features of these data include: (i) the size of data packet is at least several megabytes, e.g., a MP4 file; and (ii) these data are not planned in advance, but randomly generated during the movement. Hence, during the data delivery in VANETs, it is possible that multiple concurrent transmissions are interfered by each other, leading to retransmission or packet loss.

Each node has two transmission ranges because of the dual radios, as illustrated in Fig. 4a, which are ideally modelled as two concentric disks. Nodes share large data packets with others by WiFi radio within the short communication range r, while they exchange information by EE radio within long communication range R. Nodes fall in the scopes of the short and long transmission ranges are named as near-neighbors (NNs) and far-neighbors (FNs), respectively.

Each node keeps sharing a real-time movement information `MoveInfo` to its FNs periodically by EE radio. This information includes $< id, bx, by, v, \theta, t, ex, ey, \gamma >$, where id, (bx, by), v, θ, t, (ex, ey) and γ are the node id, the recent location, the velocity, the angle to horizontal axis, the time stamp, the end point where the node is moving to, and the

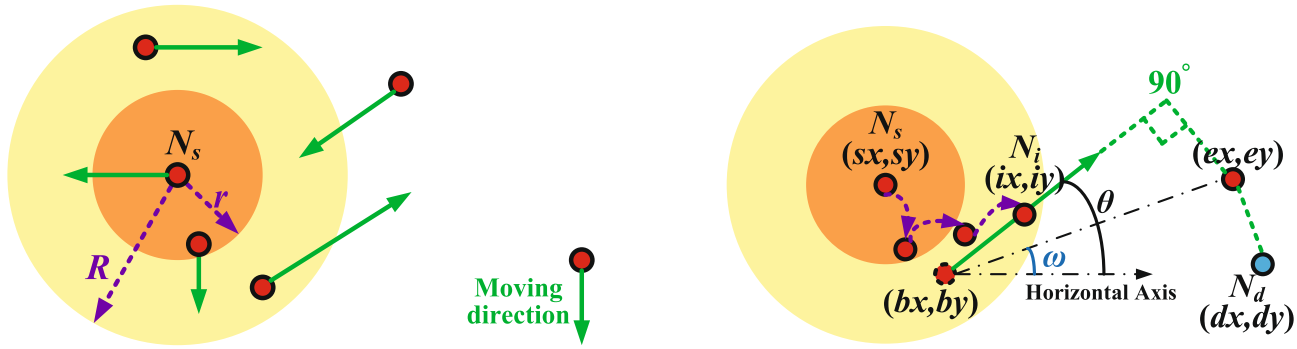


(a) The goodput in different distances between transceiver and receiver with multi-rate configuration in WiFi radio



(b) The communication range in different transmission powers with multi-rate configuration in EE radio

Fig. 3 The communication features of WiFi and EE radio, respectively



(a) The communication model of dual-radio architecture. The dash line arrow R is the communication range of long-range EE radio and r is the communication range of short-range WiFi radio. The full line arrows present the moving direction of nodes.

(b) An illustration shows the notations for next relay selection in dual-radio routing. (bx, by), (ix, iy), and (ex, ey) is N_i's beginning point, intermediate point, and end point, respectively. (dx, dy) is the location of destination node.

Fig. 4 Model of dual-radio routing protocol

selected next relay. The (ex, ey) information is an optional tuple. It may be known in some applications. e.g., in-vehicle GPS navigators allow to input the destination position (ex, ey) and compute the shortest path to there. When (ex, ey) is not known, we can use the last observed location instead. From this tuple, we infer that at time t the node *id* is on the way to (ex, ey) at the speed of v with an angle θ.

The receiver stores the `MoveInfo` got from FNs in a local n-row table, where n is the total number of mobile nodes in a VANET system. In the implementation, `MoveInfo` table is initialized with empty. If two nodes encounter in the range R, their records will be updated immediately by information exchange.

Based on the above settings, our problem is to design a routing protocol specialized for dual-radio architecture in VANETs in order to achieve the minimum delivery delay.

4.2 Design overview of dual-radio routing

As the oracle-based analysis in Jain et al. (2004), the optimal delay cannot be achieved if the future information is unknown. Hence, we develop a distributed routing algorithms to approach the $\min(T_{tot})$ using dual radios, namely dual-radio routing.

The pseudo-code of the dual-radio routing is described in Algorithm 1. The basic procedures of this algorithm include: (1) A node who would send a data packet to a destination node is named as source node N_s. Since the source node only knows the ID of the destination node, it sends the `DestID` to all far neighbors (FNs) via EE radio to request the location of the destination node. With the `DestID` together, the real-time movement information `MoveInfo` of N_s is sent. (2) After receiving the request, any FN who knows the location of destination node would response the result to N_s. (3) Based on the location of destination node and the real-time movement information, the total delivery delay via any intermediate node $T_{tot}(N_i)$ can be estimated. (4) The optimal next relay is selected from the far neighbors who leads to the minimal delivery delay. (5) In addition, the data traffic within the EE range will be considered into the `PathToNextRelay` in order to avoid transmission collision. (6) The determined `PathToNextRelay` is sent to FNs using EE radio. (7) Afterwards, the actual data is delivered from the source node to the selected relay by multi-hop of the short-range WiFi radio. Especially, if there is no suitable next relay, a node will keep carrying the data packets and selects the other relay then. (8) The procedures of (1)–(7) are repeated until that the packet arrives at the destination node.

The advantages of dual-radio routing are: (i) The next relay is selected among the FNs but not NNs. The quality of selected relay is better due to more knowledge and more candidates. (ii) The next relay γ of any neighboring node is broadcasted by the EE radio. Hence, the potential collision could be estimated and the mobile node is able to avoid the collision by selecting other relay or keeping carrying the data. (iii) The real-time movement information of all nodes in range R is known because of the information exchange in EE radio. Since the transmission speed is much higher than movement speed, the delivery delay and path from source node to the next relay can be calculated in a short period by existing deterministic routing algorithms, which we adopt the classic ED (Jain et al. 2004) in this work.

In order to reduce the energy consumption and the data traffic in VANETs, the dual-radio routing adopts single-copy pattern (Spyropoulos et al. 2008), in which each packet has only a single custodian. When a node sends a data packet to other node, this node will remove the packet from its buffer.

4.3 Design details of dual-radio routing

The main function of dual-radio routing is to select the next relay from far neighbors (FNs) within EE range. The design details of this routing solves the following problems.

Algorithm 1: Dual-Radio Routing Algorithm @ Node N_s
Input:
`DestID`: ID of destination node
`MoveInfo`: Real-time movement information
Output:
`NextRelay`, `PathToNextRelay`
Main procedure:
1: Broadcast `DestID` and `MoveInfo` to all far neighbors (FNs) using EE radio
2: Get the lastest location of destination node from FNs
3: Estimate the total delivery delay $T_{tot}(N_i)$ from the source node to the destination node via intermediate node N_i
4: Select `NextRelay` who has $\min(T_{tot}(N_i))$
5: Estimate the data traffic within the EE range
6: Determine `PathToNextRelay` and send it using EE radio
7: Send the packet according to the PathtoNextRelay using WiFi

Problem 1 How to determine the next relay from far neighbors?

The optimal next relay N_{opt} is the node belonging to far-neighbors that minimizes the expectation of total delivery delay, i.e.,

$$N_{opt} = \arg\min(T_{tot}(N_i)). \tag{1}$$

Problem 2 How to estimate the total delivery delay in dual-radio routing?

The total delivery delay from the source node N_s to the destination N_d via the intermediate node N_i can be formulated as

$$T_{tot}(N_i) = T_{S\to I}(N_s, N_i) + T_{I\to D}(N_i, N_d), \tag{2}$$

where $T_{S\to I}$ is the duration that the node N_s forwards its data packet to the node N_i in FNs, $T_{I\to D}$ is the duration that the data packet is carried or forwarded from N_i to N_d.

The value of $T_{tot}(N_i)$ is not fixed during the forward process. When a data packet is forwarded from one node to another, $T_{tot}(N_i)$ will be re-calculated according to dynamic neighbors. Thus, the data packet could gradually approach the destination node.

To calculate the total delivery delay $T_{tot}(N_i)$, we have the following analysis and derivation.

Problem 3 How to estimate $T_{S\to I}(N_s, N_i)$?

Since we have the real-time `MoveInfo` of all FNs, $T_{S\to I}(N_s, N_i)$ can be estimated. In details, we first assume that the movement of any node maintains its trend including direction, velocity, and acceleration within a short while. Then, we try to build the Dijkstra's shortest path between the source node and any FN by a multi-hop WiFi manner. The edge in the shortest path takes the movement and communication range r into account. In this way, we can judge whether a packet from N_s to N_i is reachable. If it is reachable, we can calculate $T_{S\to I}(N_s, N_i)$ using the shortest path.

Moreover, it is easy to observe that the delivery delay of a packet from the source node to the intermediate node $T_{S\to I}(N_s, N_i)$ is equal to the duration of N_i moving from the beginning point to the intermediate point $T_{B\to I}(N_i)$ as shown in Fig. 4b.

Problem 4 How to estimate $T_{I\to D}(N_i, N_d)$?

It is difficult to estimate $T_{I\to D}(N_i, N_d)$ directly due to lack of information out of EE range. Hence, we transfer the expression of $T_{tot}(N_i)$ and provide the theoretical upper bound from another direction.

Theorem 1 *If $T_{S\to I}(N_s, N_i)$ is finite (i.e., packet from N_s to N_i is reachable), $T_{tot}(N_i)$ can be also expressed by*

$$T_{tot}(N_i) = T_{B\to E}(N_i) + T_{E\to D}(N_i, N_d), \tag{3}$$

where $T_{B\to E}$ is the duration that the node N_i moves from its beginning point (bx, by) to its end point (ex, ey), and $T_{E\to D}$ is the duration that the data packet is transmitted from N_i at (ex, ey) to the destination node N_d, where (dx, dy) is the last recorded location of the destination node.

Proof If $T_{S\to I}(N_s, N_i)$ is finite, then

$$T_{I\to D}(N_i, N_d) = T_{I\to E}(N_i) + T_{E\to D}(N_i, N_d), \tag{4}$$

where $T_{I\to E}$ is the duration that N_i travels from the intermediate point (ix, iy) to the end point (ex, ey) as illustrated in Fig. 4b. Since $T_{S\to I}(N_s, N_i) = T_{B\to I}(N_i)$,

$$T_{I\to E}(N_i) = T_{B\to E}(N_i) - T_{S\to I}(N_s, N_i). \tag{5}$$

Substituting Eqs. 4 and 5 to Eq. 2, we get Eq. 3. □

Recall that each node has the `MoveInfo` table, with which we can derive the upper bound of Eq. 3 via the following two theorems.

Problem 5 How to estimate the upper bound of $T_{B\to E}(N_i)$?

Theorem 2 *The upper bound of $T_{B\to E}(N_i)$ equals to L / v, where*

$$L = \begin{cases} (\sin|\theta-\omega| + \cos|\theta-\omega|)\times \\ \sqrt{(ex-bx)^2+(ey-by)^2}, & |\theta-\omega| < 90°, \\ \infty, & \text{otherwise}, \end{cases} \quad (6)$$

ω is $\arctan(\frac{ey-by}{ex-bx})$, *and θ is the recent moving angle of N_i.*

Proof The upper bound of $T_{B\to E}(N_i)$ is the duration that N_i moves from its beginning point (bx, by) to end point (ex, ey). Since the transmission speed via WiFi is always faster than the movement speed, the upper bound of delivery delay is that N_i carries the data packet itself to the end point. If $|\theta-\omega| \geq 90°$ (i.e., if node N_i is moving away from its end point temporarily), we do not use it for relaying and set $T_{B\to E}(N_i) = \infty$. However, this node is possible to be selected in the future, if this node turns back to the path between another relay and the destination node. When $|\theta-\omega| < 90°$, the longest distance is the sum of the two right-angle sides as shown in Fig. 4b, which is trivial to be calculated using triangle equations. This longest distance can be further bounded if the map information is known. We can calculate it as the total distance of the shortest path between (bx, by) and (ex, ey) subject to the road map. □

Problem 6 How to estimate the upper bound of $T_{E\to D}(N_i, N_d)$?

Theorem 3 *The upper bound of* $T_{E\to D}(N_i, N_d)$ is

$$T_{E\to D}(N_i, N_d) = \frac{\sqrt{(dy-ey)^2+(dx-ex)^2}}{\overline{v}}, \quad (7)$$

where $\overline{v} = \frac{\sum_{i=1}^{n} v_i}{n}$ *is the average velocity of all the nodes in this VANET, and v_i is the velocity of node N_i.*

Proof The upper bound of $T_{E\to D}(N_i, N_d)$ is the duration that a node carriers the data packet and moves from N_i's end point (ex, ey) to the location of destination node (dx, dy). Since the EE radio cannot cover the whole area of VANET, we use the average velocity of all the nodes to approach the velocity from (ex, ey) to (dx, dy). Moreover, as Theorem 2, we consider the upper bound duration is that a packet is carried rather than transmitted. Above all, we have Eq. 7. □

Problem 7 How to reduce the collision of data delivery?

On one hand, we adopt a single-copy routing method. i.e., a data packet has only one path to be delivered. Hence, the total traffic load of the VANET is minimized, which reduces the probability of collisions. On the other hand, using the real-time movement information of all nodes `MoveInfo` and other nodes' `PathToNextRelay`, a node can predict the others' transmissions within a short while. Thus, the path selection could consider and bypass the hot spot to reduce the collisions.

In the end of this section, we discuss the computational complexity of the proposed dual-radio routing. After analyzing Algorithm 1, we find that the complexity is $O(n \log n)$ because the dominated function in dual-radio routing is Dijkstra's shortest path, whose complexity is widely proved as $O(n \log n)$.

5 Prototype implementation and experiment

We implement the dual-radio routing in our platform. Then, we conduct testbed based experiments to evaluate the performance.

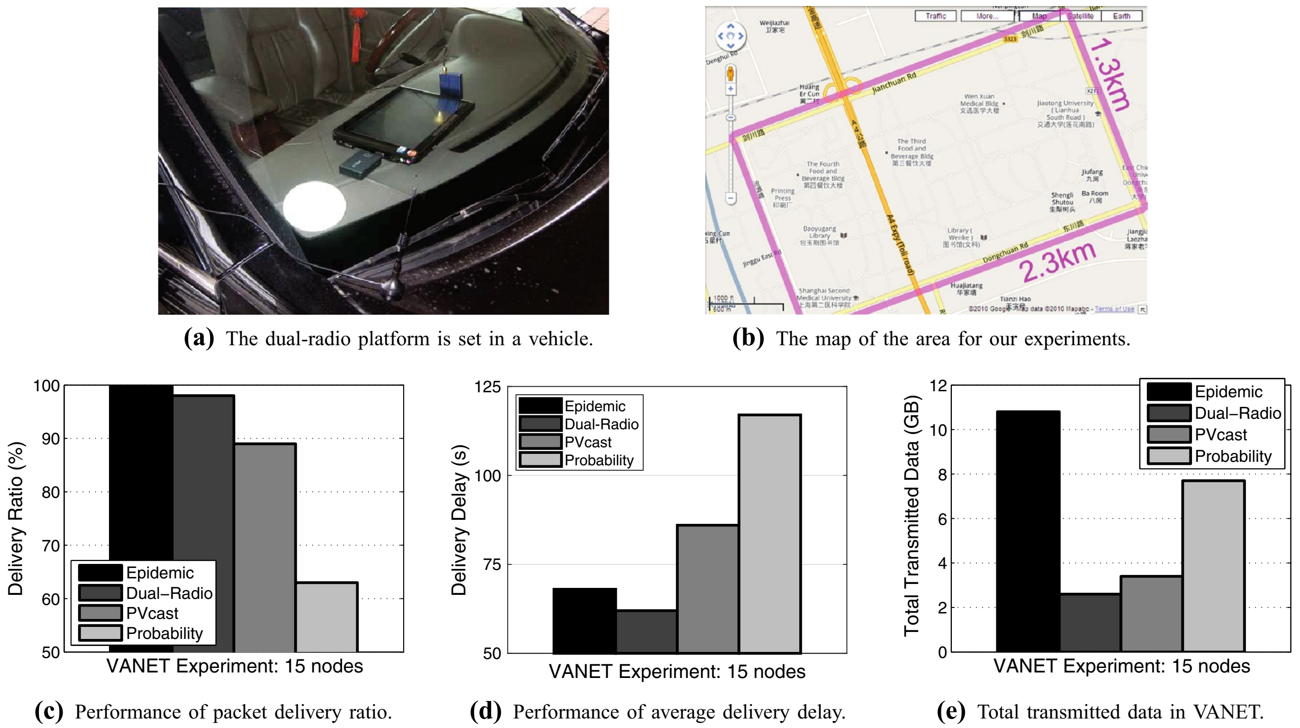
5.1 Prototype configuration

We build a 16-node testbed using our dual-radio platforms. Each node is carried by a vehicle as shown in Fig. 5a. All vehicles randomly move in the campus whose area is $2.3 \times 1.3\,\text{km}^2$ as shown in Fig. 5c.

In our experiment, the long-range EE radio operates in 433 MHz band, 20mW transmission power, and 19.2 Kbps data rate. Thus, its communication range is about 800 m. The short-range WiFi radio operates at 20 MHz channel in 2.422 GHz band and 100 mW transmission power. Its data rate is adaptive from 6 to 54 Mbps according to the channel quality. The communication range of WiFi is less than 200 m as shown in Fig. 3a. All nodes adopt the unified GPS time, thus they are synchronous. We leverage the CSMA/CA mechanism in EE radio to avoid signal collisions. Since the movement information `MoveInfo` of each node is a 9-tuple message whose size is $9 \times 4 = 36$ Bytes and the broadcast interval is configured as 1 second, the data rate 19.2 Kbps with CSMA/CA is sufficient to support 15 nodes' communications, even there are some retransmissions. Using the following equation, we find that our configuration can theoretically support 66 mobile nodes, which is much larger than 15 nodes.

$$\frac{19.2\,\text{Kbps}}{36\,\text{Bytes} \times 8\,\text{bits} \times 1\,\text{s}} = 66.67 > 15 \quad (8)$$

We conduct our experiments totally 12 h and evaluate three routing algorithms, respectively. These four algorithms are dual-radio routing, epidemic routing (Zhang et al. 2007), probability routing (Spyropoulos et al. 2008), and PVcast (Xiang et al. 2015). Except dual-radio, the other three routing protocols use only the WiFi radio. The classic



(a) The dual-radio platform is set in a vehicle. **(b)** The map of the area for our experiments.

(c) Performance of packet delivery ratio. **(d)** Performance of average delivery delay. **(e)** Total transmitted data in VANET.

Fig. 5 The results of implementation and experiments

epidemic routing is a flooding based routing protocol, in which a vehicle delivers the data packet to all encountered vehicles to increase the delivery ratio. However, its energy consumption is high and may lead to broadcast storm. To reduce the traffic load in VANET, the probability routing is proposed, in which a vehicle delivers the data packet with a preset probability. In our experiment, we set that any node forwards the packet to non-destination node with probability $p = 0.5$ and to a destination node with $p = 1$. The state-of-the-art PVcast uses WiFi for not only the data delivery but also the movement information exchange. Compared with PVcast, dual-radio obtains more `MoveInfo` due to its long-range EE and lower load in WiFi radio due to only data delivery tasks. In all experiments, each node generates a 4MB MP3 file every minute and sends to a random ID node as destination. A data packet is considered as lost if it never reaches the destination or the number of its forwarded times is larger than a TTL (Time-to-Live) threshold (Jain et al. 2004). We set the value of TTL is 16, which is a little larger than the number of nodes.

5.2 Experiment results

Figure 5c compares the packet delivery ratios of the four routing algorithms. We find that almost all packets, nearly 98%, are successfully delivered in dual-radio routing. The epidemic routing achieves 100% delivery ratio due to its flooding mechanism. Only 63% data packets arrive at the destination nodes in the probability routing algorithm. The possible reason is that its forwarding number is easy to exceed the preset TTL. PVcast delivers more than 89% packets to the destination nodes. Compared dual-radio, PVcast has shorter view to find optimal next relay, leading to a lower delivery ratio. This result demonstrate that the proposed dual-radio routing protocol ensures the delivery ratio in VANETs.

In Fig. 5d, we illustrate the average packet delay during our experiments. In epidemic routing, the delivery delay is defined as the duration from the data packet sent by the source to its first duplication received by the destination. It can be seen that our dual-radio achieves 62-second delay in average. The epidemic routing is a little higher, at 68s, because the concurrent transmission of multiple copies lead to collisions. The probability routing incurs the highest delay 117s due to some longer walk. The performance of PVcast is between epidemic and probablity, which is about 86s.

In Fig. 5e, we plot the total amount of packet transmitted in the whole network. This figure shows the advantage of dual-radio routing against the epidemic routing. In order to achieve the similar delivery ratio and average delay shown in Fig. 5d, e, the dual-radio routing transmit only 25% amount of data compared with epidemic. In particular, the epidemic routing transmits 10.8 GB data totally.

The dual-radio only transmits 2.6 GB, outperforming the probability routing's 7.7 GB and PVcast's 3.4 GB.

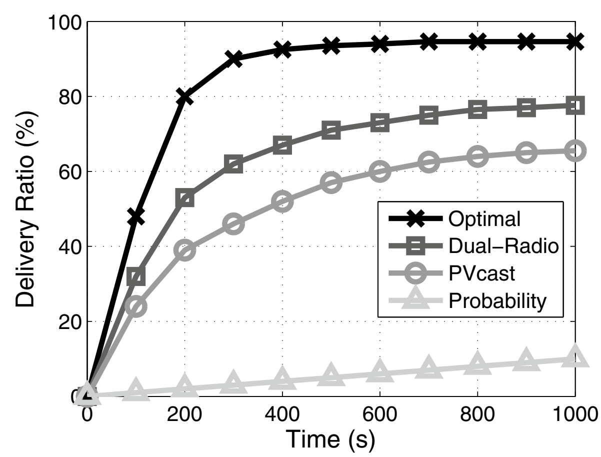
6 Simulation

Our experiment is limited by the limited area and number of vehicles. In order to understand the performance of dual-radio architecture and routing in large-scale VANETs, we carry out extensive simulations based on real taxi traces in Shanghai urban.

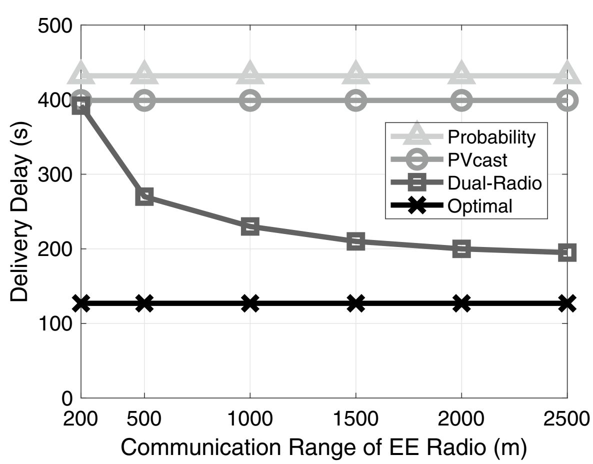
6.1 Simulation settings

The taxi traces in Shanghai urban are collected by SUVnet project (Huang et al. 2007). In this project, more than 4000 taxis equipped with GPS report their id, location, time stamp, speed, direction, and loading state in a fixed interval time. From this data, we selected the downtown area of Shanghai with an area of about 102 km^2 as shown in Fig. 6a. Since the SUVnet is an open system in which taxis entered and left the area of interests from time to time, the actual number of taxis varies from 2380 to 2937 in our simulations. The TTL can be set by the user according to the application. In our simulation, we set it as 100 by default. Moreover, when the whole network becomes congestion, it is possible that the buffer in nodes will run out. To address this problem,

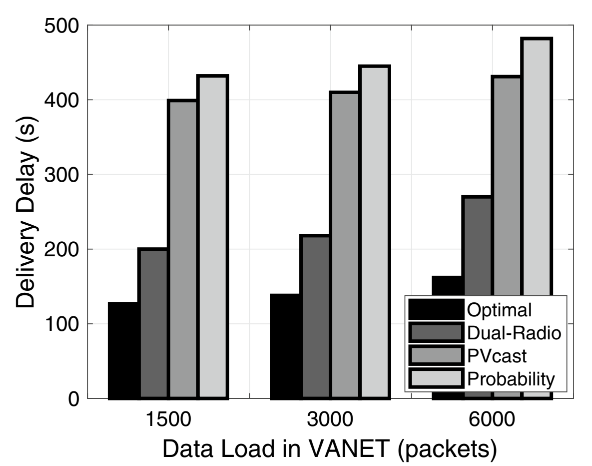
(a) The Shanghai map, in which the rectangle area is used for our simulations.



(b) CDF of the packet delivery ratio when the simulation time varies from 0 to 1000 seconds.



(c) The average delivery delay when the EE range R varies from 200m to 2500m.



(d) The average delivery delay when the number of sending packets in the first 5 minutes is 1500, 3000, and 6000, respectively.

Fig. 6 The simulation results regarding delivery ratio and average delay, together with parameter sensitivity analysis

Table 3 Specific simulation settings

Simulation parameters	Value
EE radio range R	2000 m
WiFi radio range r	200 m
EE data rate	19.2 Kbps
WiFi data rate	6 Mbps
Data packet size	1 MB
Packet number per minute	300 packets on average
Source nodes	Randomly selected
Destination nodes	Randomly selected
Node receive buffer size	32 MB
Time-to-live (TTL)	100 forward times

when the buffer is full, we remove the data packet with the largest TTL. Table 3 illustrates the simulation initialization.

In order to evaluate the performance of dual-radio routing, we select three existing algorithms as baselines: probability routing (Spyropoulos et al. 2008), PVcast (Xiang et al. 2015), and theoretical optimal routing. The probability routing and PVcast are the same as the experiments. Unlike the experiments, we do not adopt the epidemic routing in simulations because it is heavily resource-consuming and may incur serious network congestions in the dense scenario. Instead, the theoretical optimal routing is derived from epidemic spread, but assumes that the buffer and bandwidth are infinite in simulations. Thus, the duration of first copy arriving at the destination node is the theoretical minimum delivery delay.

6.2 Performance analysis

The CDF of the packet delivery ratio is illustrated in Fig. 6b. Since partial taxis drive in and out of the considered area, packets carried by them never reach the destination nodes. Consequently, each routing algorithm suffers from some packet loss. Even the optimal algorithm performs only 94.6% delivery ratio. Figure 6b also indicates that our dual-radio routing dramatically enhance the delivery ratio, compared with PVcast and probability routing. Especially, the ratio difference between dual-radio and the optimal is about 17%.

We then validate the impact of the communication range R using EE radio. Figure 6c draws the delivery delay with the increase of R from 200 to 2500 m. The performance probability, PVcast, and optimal routings remain the same since they have no long-range radio. As expectation, the dual-radio routing achieves lower delivery delay with the increase of R. Theoretically, when R gets infinite, the EE radio can get the global movement information of all nodes, approaching the optimal next relay selection. When both R and r are 200 m, the delivery delays for dual-radio routing and PVcast are 392 s and 399 s, respectively. Benefiting from the information exchange on EE radio, the dual-radio routing achieves better results than PVcast, whose information exchange still needs to occupy partial resource of WiFi. When R reaches the longest 2500 m, the average delivery delay is 195 s for dual-radio routing, which reduces up to 50% delay by using the dual-radio architecture.

Finally, to evaluate the impact of the network load, we change the number of generated packets to be 1500, 3000 and 6000 in the first 5 min. The results in Fig. 6f demonstrate that heavier traffic load leads to a higher packet delivery delay. The reason is that the large amount of concurrent transmissions result in plenty of collisions and retransmissions. Moreover, the dual-radio routing algorithms outperform the others with respect to the traffic load.

7 Conclusion

In this paper, we study the enhancement of the data packet delivery in VANETs for intelligent transportation systems. We design a dual-radio architecture, in which the WiFi radio transmits data and an additional long-range low-rate EE radio exchanges the movement information. This EE radio can cover range much larger than WiFi does. We further propose a dual-radio routing algorithm, which fundamentally avoids the transmission collision by selecting the optimal next relay nodes with minimum expected deliver delay. Both prototype implementation and real trace-based simulation results demonstrate that the proposed architecture and algorithm outperform existing methods.

The dual-radio architecture could be further improved by the following future works. First, the EE radio only supports one-hop far-neighbor query. It is better to extend it to multi-hop communications for obtaining more movement information. Second, leveraging the information from EE radio, it is promising to design a joint optimization between power control and rate adaptation for WiFi radio to further improve the delivery performance. Third, introducing more wireless protocol such as DSRC and LTE into our architecture is also our future work.

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References

Abdelkader, T., Naik, K., Nayak, A., Goel, N., Srivastava, V.: SGBR: a routing protocol for delay tolerant networks using social grouping. IEEE Trans. Parallel Distrib. Syst. **24**(12), 2472–2481 (2013)

Altman, E., Sassatelli, L., De Pellegrini, F.: Dynamic control of coding for progressive packet arrivals in DTNs. IEEE Trans. Wirel. Commun. **12**(2), 725–735 (2013)

Banerjee, N., Corner, M.D., Levine, B.N.: Design and field experimentation of an energy-efficient architecture for DTN throwboxes. IEEE/ACM Trans. Netw. **18**(2), 554–567 (2010)

Chen, X., Kong, L., Liu, X., Rao, L., Bai, F., Xiang, Q.: How cars talk louder, clearer and fairer: optimizing the communication performance of connected vehicles via online synchronous control. In: IEEE INFOCOM (2016)

Dhananjay, A., Zhang, H., Li, J., Subramanian, L.: Practical, distributed channel assignment and routing in dual-radio mesh networks. ACM SIGCOMM Comput. Commun. Rev. **39**(4), 99–110 (2009)

Gao, W., Cao, G., La Porta, T., Han, J.: On exploiting transient social contact patterns for data forwarding in delay-tolerant networks. IEEE Trans. Mobile Comput. **12**(1), 151–165 (2013)

Gao, W., Li, Q., Zhao, B., Cao, G.: Multicasting in delay tolerant networks: a social network perspective. In: ACM MobiHoc (2009)

Hartenstein, H., Laberteaux, L.: A tutorial survey on vehicular ad hoc networks. IEEE Commun. Mag. **46**(6), 164–171 (2008)

Huang, H.-Y., Luo, P.-E., Li, M., Li, D., Li, X., Shu, W., Wu, M.-Y.: Performance evaluation of suvnet with real-time traffic data. IEEE Trans. Veh. Technol. **56**(6), 3381–3396 (2007)

Hui, P., Crowcroft, J., Yoneki, E.: Bubble rap: social-based forwarding in delay-tolerant networks. IEEE Trans. Mobile Comput. **10**(11), 1576–1589 (2011)

Jain, S., Fall, K., Patra, R.: Routing in a delay tolerant network. In: ACM SIGCOMM (2004)

Ji, S., Li, Y., Jia, X.: Capacity of dual-radio multi-channel wireless sensor networks for continuous data collection. In: IEEE INFOCOM (2011)

Jones, E.P., Li, L., Schmidtke, J.K., Ward, P.A.: Practical routing in delay-tolerant networks. IEEE Trans. Mobile Comput. **6**(8), 943–959 (2007)

Kong, L., Khan, M.K., Wu, F., Chen, G., Zeng, P.: Millimeter-wave wireless communications for IoT-cloud supported autonomous vehicles: overview, design, and challenges. IEEE Commun. Mag. **55**(1), 62–68 (2017)

Li, Y., Su, G., Wu, D., Jin, D., Su, L., Zeng, L.: The impact of node selfishness on multicasting in delay tolerant networks. IEEE Trans. Veh. Technol. **60**(5), 2224–2238 (2011)

Lin, D., Kang, J., Squicciarini, A., Wu, Y., Gurung, S., Tonguz, O.: Mozo: a moving zone based routing protocol using pure v2v communication in vanets. IEEE Trans. Mobile Comput. **16**(5), 1357–1370 (2017)

Musolesi, M., Mascolo, C.: Car: context-aware adaptive routing for delay-tolerant mobile networks. IEEE Trans. Mobile Comput. **8**(2), 246–260 (2009)

Polese, M., Giordani, M., Mezzavilla, M., Rangan, S., Zorzi, M.: Improved handover through dual connectivity in 5g mmwave mobile networks. IEEE J. Sel. Areas Commun. **35**(9), 2069–2084 (2017)

Silva, A.P., Burleigh, S., Hirata, C.M., Obraczka, K.: A survey on congestion control for delay and disruption tolerant networks. Ad Hoc Netw. **25**, 480–494 (2015)

Singh, C., Altman, E., Kumar, A., Sundaresan, R.: Optimal forwarding in delay-tolerant networks with multiple destinations. IEEE/ACM Trans. Netw. **21**(6), 1812–1826 (2013)

Soares, V.N., Rodrigues, J.J., Farahmand, F.: Geospray: a geographic routing protocol for vehicular delay-tolerant networks. Inf. Fusion **15**, 102–113 (2014)

Spyropoulos, T., Psounis, K., Raghavendra, C.S.: Efficient routing in intermittently connected mobile networks: the single-copy case. IEEE/ACM Trans. Netw. **16**(1), 63–76 (2008)

Spyropoulos, T., Psounis, K., Raghavendra, C.S.: Spray and wait: an efficient routing scheme for intermittently connected mobile networks. In: ACM SIGCOMM Workshop on Delay-Tolerant Networking (2005)

Talipov, E., Chon, Y., Cha, H.: Content sharing over smartphone-based delay-tolerant networks. IEEE Trans. Mobile Comput. **12**(3), 581–595 (2013)

Wang, B., Kong, L., He, L., Wu, F., Yu, J., Chen, G.: I(TS,CS): Detecting faulty location data in mobile crowdsensing. In: IEEE ICDCS (2018)

Xiang, Q., Chen, X., Kong, L., Rao, L., Liu, X.: Data preference matters: a new perspective of safety data dissemination in vehicular ad hoc networks. In: IEEE INFOCOM, (2015)

Xiao, M., Wu, J., Liu, C., Huang, L.: Tour: time-sensitive opportunistic utility-based routing in delay tolerant networks. In: IEEE INFOCOM (2013)

Zeng, D., Guo, S., Hu, J.: Reliable bulk-data dissemination in delay tolerant networks. IEEE Trans. Parallel Distrib. Syst. **25**(8), 2180–2189 (2014)

Zeng, Y., Xiang, K., Li, D., Vasilakos, A.: Directional routing and scheduling for green vehicular delay tolerant networks. Wirel Netw **19**(2), 161–173 (2013)

Zhang, X., Neglia, G., Kurose, J., Towsley, D.: Performance modeling of epidemic routing. Comput. Netw. **51**(10), 2867–2891 (2007)

Zhang, X., Neglia, G., Kurose, J., Towsley, D., Wang, H.: Benefits of network coding for unicast application in disruption-tolerant networks. IEEE/ACM Trans. Netw. **21**(5), 1407–1420 (2013)

Zhou, R., Xiong, Y., Xing, G., Sun, L., Ma, J.: Zifi: wireless LAN discovery via ZigBee interference signatures. In: ACM MOBICOM (2010)

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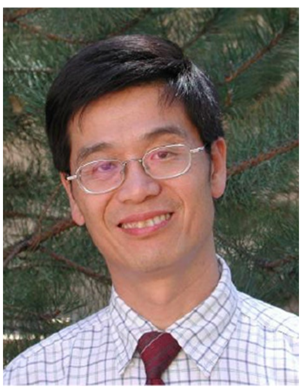

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