# Data Dissemination in VANETs: A Scheduling Approach

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***Abstract*—Data dissemination is a promising application for the vehicular network. Existing data dissemination schemes are generally built upon some random-access protocol, which results in the unavoidable collision problem. To address this problem, in this paper we design a novel data dissemination strategy from the scheduling perspective. A data dissemination scheduling framework is then proposed. In the proposed framework, the main challenge is how best to assign the transmission opportunity to nodes with maximum dissemination utility and to avoid the collision problem. We then propose a novel and practical relay selection strategy and adopt the space–time network coding (STNC) with low detection complexity and space–time diversity gain to improve the dissemination efficiency. Compared with the random-access dissemination such as CodeOn-Basic and the noncooperative transmission, our proposed data dissemination strategy performs better in terms of the dissemination delay. In addition, the proposed strategy works even better in the dense network than the sparse scenario, benefitting from the space–time diversity gain of STNC and no-collision transmissions. This is in sharp contrary to the CodeOn-Basic method.**

***Index Terms*—Cooperative communication, data dissemination, relay selection, space–time network coding, vehicular ad hoc network (VANET).**

## I. Introduction

VEHICULAR ad hoc networks (VANETs) consist of a cornerstone of the modern intelligent transportation system (ITS) by allowing the vehicles to communicate with each other via vehicle-to-vehicle (V2V) communications as well as with roadside units (RSUs) via vehicle-to-infrastructure (V2I) communications [1], [2]. It is envisioned that the ITS technology can revolutionize the quality of experience for the drivers and passengers by enabling a broad array of road safety and traffic efficiency applications, e.g., safety warning, smart parking, and intelligent navigation. A particularly promising application is the data dissemination related to both the safety and commercial services to vehicles. That is, vehicles inside a geographical area of interest (AoI) attempt to obtain some common information, such as local weather, congestion status, or local business advertisement, from the RSU. A more important functionality for the RSU is to inform vehicles of the real-time traffic status and collision warnings such that the driver or the intelligent driving system can respond in time to avoid accidents. The primary requirement for the data dissemination in VANETs is to minimize the dissemination delay as much as possible. The dissemination delay refers to the duration from the start of data dissemination to the time when all the vehicles in the AoI successfully decode the entire data set. However, it is nontrivial to design low-latency data dissemination strategies for VANETs because the mobile channel [3]–[6] is highly time variant, and the V2V channel modeling [7]–[9] is still very challenging in the current literature.

Many existing data dissemination strategies [10]–[22] are generally built upon some random-channel-access protocol [23] considering the highly time-varying topology characterizing VANETs. Nevertheless, they all encounter issues such as the random interaction for transmission requests or decoding status exchange among vehicles, as well as the inevitable collision problem. Attempting to resolve those issues, we first put forward a data dissemination scheduling strategy based on a novel application of space–time network coding (STNC) [24]. In this paper, the proposed scheduling strategy is controlled by a central server (CS) for scheduling the transmission frames to vehicles and avoiding the collision problem. Note that, although drastically different from the prevalent random access in the literature, our proposed scheduling strategy is actually quite reasonable since the RSU usually has full knowledge of the vehicle topology within its coverage. When the RSU gets informed of the velocity information, the RSU can monitor the topology change. Therefore, one can actually carry out the scheduling function as a cellular network. For the proposed scheduling strategy, the basic idea is to let the CS select relay nodes and assign the corresponding transmission frames for them. Evidently, the data dissemination utility of each node gets constantly changed throughout the data transmission.

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Therefore, the main challenge is to design an effective relay selection algorithm to choose the node with the maximum dissemination utility for each transmission frame. Fully exploiting the scheduling advantage for data dissemination necessitates nontrivial protocol design, toward which we make the following main contributions.

1) We propose a data dissemination approach from a scheduling perspective for the VANETs. This is to be contrasted with conventional approaches based on the random-channel-access protocol. Unlike the traditional scheduling problem in a cellular network, where the radio channel is allocated for either downlink or uplink communication, the scheduling problem in the VANETs further exploits the benefit of V2V communication in addition to the V2I communication. V2V communication can cooperate with the V2I communication to improve the data dissemination efficiency by allowing vehicles to share the data with neighboring vehicles. Compared with the noncooperative method, where the data are transmitted by the RSU only, the proposed cooperative method performs better in terms of the data dissemination delay, as shown in Section V by simulations.
2) We design a framework for scheduling the transmission frames to vehicles. To catch the real-time-varying topology, each vehicle should periodically update the velocity and position information to the RSU. The unit of the proposed framework is the so termed data dissemination cycle. It consists of three phases: 1) relay selection phase, where the CS first schedules the transmission frames for all the nodes in the AoI including both vehicles and RSUs; 2) relay transmission phase, where each selected relay node transmits data with the assigned frame; and 3) feedback phase, where vehicles feed back the decoding status and current velocity and position information for the CS to carry out the scheduling function for the next cycle.
3) We apply STNC for data transmission in this paper. Unlike the random linear network coding (RLNC) [25] and fountain codes [26], the coding coefficients for the coded packet are generated according to the code-division multiple-access protocol, and thus, the signal can be detected by a simple matched filtering method. In addition, the signal detection can further exploit the space–time diversity to improve the successful decoding probability.
4) We design a practical relay selection strategy based on the knowledge of velocity, position, and decoding status. In each transmission frame, the node with maximum utility is selected for data relaying. The performance of our proposed strategy is then evaluated by simulations. Compared with the CodeOn-Basic method proposed in [13], the proposed strategy not only performs better due to the noncollision transmission but also performs even better in the dense network than the sparse scenario. This is because under the dense condition, the advantage of the space diversity in the STNC can be further exploited. Compared with the sparse network, more suitable nodes can be selected for data relaying with STNC in the dense scenario.

The rest of this paper is organized as follows: Section II outlines the related work on the data dissemination in VANETs. Section III describes the system model, including a brief introduction of the scheduling method and the adopted STNC method. The proposed data dissemination scheduling strategy is provided in Section IV. Section V provides the simulation results and discussions. Conclusions are drawn in Section VI.

## II. Related Work

Nandan *et al.* first introduced a pull-based data-downloading method for VANETs in [10], namely, the swarming protocol for vehicular ad hoc wireless networks (SPAWN). Using SPAWN, a vehicle requests the data from the RSU if it is within the RSU range or from neighboring vehicles with a peer-to-peer protocol when it moves out of the RSU range. In [11], SPAWN was extended to the push-based method named AdTorrent where the RSU continuously broadcasts the common information to the vehicles within its coverage. While for the peer-to-peer communication among vehicles, the provider delivers top-ranked content to the end user using swarming. In both SPAWN and AdTorrent, the multihop peer-to-peer transmission with a transmission control protocol will result in high overhead and poorly performs over the highly mobile lossy wireless links in VANETs.

In [12], Lee *et al.* presented a novel strategy called CodeTorrent based on RLNC. CodeTorrent is also a pull-based method where nodes send requests for data access. Unlike SPAWN [10], CodeTorrent restricts data sharing to the one-hop neighborhood of a vehicle, thus eliminating the multihop and route selection problem. Based on CodeTorrent, Li *et al.* put forward a push-based method called CodeOn [13], which is also based on RLNC. In CodeOn, each node exchanges the decoding status with their one-hop neighbors and then calculates its data rebroadcasting utility for neighbors. The greater the utility, the smaller the waiting time before data relaying. CodeOn was then further improved by incorporating the channel state into the utility [14]. Moreover, a secure data dissemination strategy with RLNC was put forward in [15].

In [16], Sardari *et al.* adopted the fountain code for data dissemination in VANETs. In [17], Stefanovic *et al.* presented a solution for data dissemination by using expanding window fountain codes [27], which are rateless codes with the unequal error protection property. However, the solution provided in [17] is noncooperative by using only V2I communication, which may reduce the dissemination efficiency. In [18], Palma *et al.* further designed a cooperative generation matrix to generate the coded packets with a fountain code to reduce the decoding complexity.

In addition, Zhang *et al.* [19] proposed a VC-MAC protocol for data downloading from the RSU gateway. The relay selection in VC-MAC for maximizing the system throughput is not content aware, which may cause the selected relay node to have nothing innovative to its neighbors. Cenerario *et al.* [20] exploited the encounter probability to decide when a rediffusion is needed at the intermediate vehicle in the dissemination protocol. Ros *et al.* [21] presented an acknowledgement-based broadcasting protocol to let the node in a connected dominating set transmit data with high priority. Wu *et al.* [22] put forward a hybrid routing scheme for data dissemination based on the maximum distance separation code.

Although these random-access data dissemination strategies can adapt to the mobile vehicular network, there still exist some issues deteriorating the performance. The first issue is the random interaction for transmission requests [10], [12] or decoding status [13] exchange among vehicles. Generally, a vehicle cannot receive the information from all the neighbors simultaneously. As a result, the transmission response by the vehicle is not accurate. However, if a vehicle responds to the transmission request only after collecting information from all the neighbors, it certainly enlarges the data dissemination delay. The second issue is the unavoidable collision problem. When the network gets dense, the transmission collisions happen with high probability with a random-channel-access protocol. It will result in retransmission and further intensify the collisions. Moreover, the currently widely used network coding (NC) methods to improve the dissemination efficiency, i.e., RLNC and fountain codes also face application challenges. In addition to the complex signal detection, in both RLNC and fountain codes, the receiver should successfully detect at least independent $N$ coded packets before decoding the original $N$ packets. However, it is very difficult to collect enough coded packets with large $N$ and dense network situation due to the collision problem. The dissemination delay performance then gets negatively affected.

## III. System Description

In this paper, we consider the general system model of data dissemination in the VANETs, where the RSU is the data resource, and vehicles inside the AoI are the end receivers. Each RSU connects with the core Internet through the wired backhaul. The data dissemination involves two types of communication: 1) V2I communication, where the RSU broadcasts the data to the vehicles within its coverage; and 2) V2V communication, where the vehicle can share data with the neighboring nodes. We assume that within the AoI, there are $P$ RSUs denoted as $\mathbf{RSU} = \{RSU_1, RSU_2, \ldots, RSU_P\}$ and $K$ vehicles denoted as $\mathbf{U} = \{U_1, U_2, \ldots, U_K\}$. Each vehicle carries the Global Positioning System receiver to obtain its position. Moreover, all nodes are synchronous in time for data transmission. Assume that the control signal involved in the data dissemination is transmitted with the control channel and that the data to be disseminated are carried by the service channel. In addition, the control channels are assumed to be error free, and thus, the control signal can be reliably decoded.

### A. Scheduling Approach

The proposed scheduling approach is carried out by a control node. The duty of the control node is to select proper relay nodes and assign the transmission frames for them. Since the RSU has complete knowledge of the vehicle topology within its coverage and can trace the varying topology if knowing the velocity information, we can make the RSU the control node to schedule the most useful relay nodes for the data dissemination. However, transmission collision may still occur at the range

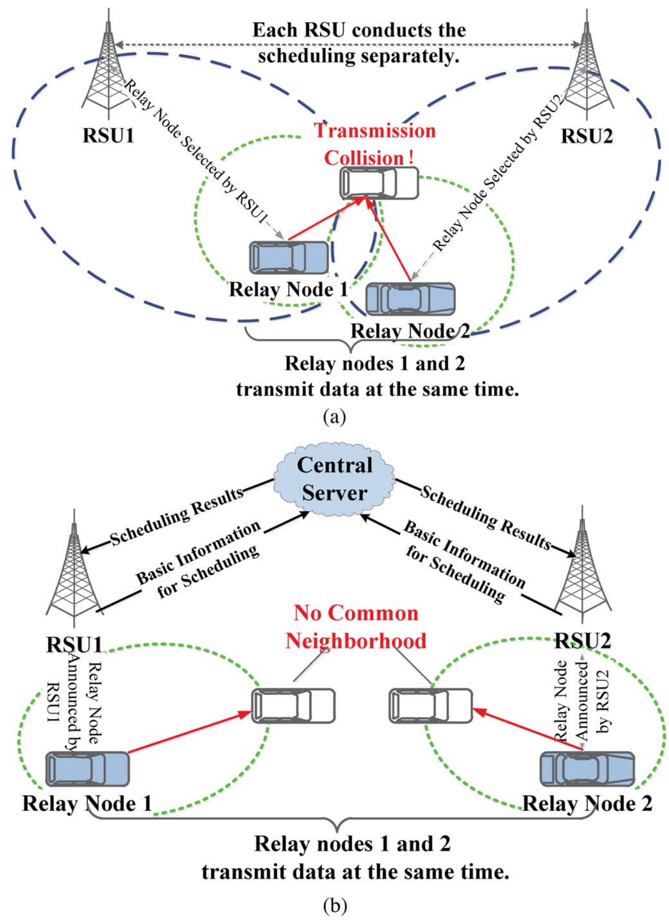


Fig. 1. (a) Collision illustration when the RSUs select relay nodes separately. (b) Collision avoidance with the CS.

edge, as shown in Fig. 1(a), where relay node 1 selected by RSU1 and relay node 2 selected by RSU2 may have common neighboring vehicles. A receiving collision then will occur to the common neighbor if relay nodes 1 and 2 are scheduled to transmit the data at the same time.

To avoid this kind of collision, we adopt a CS that connects with the RSUs with a wired backhaul to make the scheduling decision for each RSU, as shown in Fig. 1(b). The CS could also be an RSU. Each RSU should provide the basic information for the scheduling to the CS. The basic information includes velocity, position, and decoding status of vehicles in the AoI. How to make use of such information to carry out the scheduling at the CS will be described later in Section IV. Unlike RSUs, which only have the scope of vehicle topology in their coverage, the CS has the entire scope of vehicle topology in the AoI. Therefore, the aforementioned collision problem can be avoided by inserting the constraint that the relay nodes assigned with the same transmission frame have no common neighbors into the scheduling decision, as shown in Fig. 1(b). The CS then informs the RSUs of the scheduling results, and each RSU just announces the results to the vehicles within its coverage.

### B. STNC

Without loss of generality, the NC tool is also implemented in the proposed data dissemination strategy to improve the

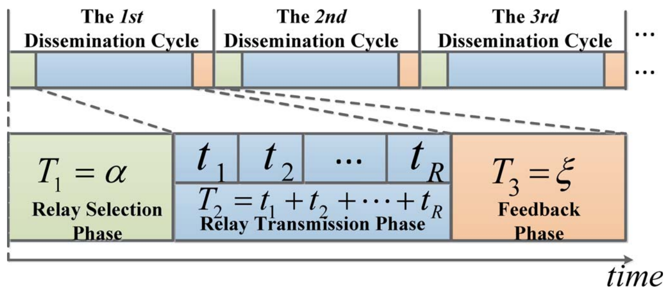


Fig. 2. Proposed data dissemination framework for the VANETs.

dissemination efficiency. NC is usually applied for data broadcasting without acknowledgment since it can effectively reduce redundant transmissions and simplify the transmission scheduling [28], [29]. However, due to the complex decoding issues of the traditional NC tools, i.e., RLNC and fountain codes, we resort to a simpler new NC method, namely, STNC. Assume that there are $N$ packets, i.e., $\mathbf{X} = \{X_n | n = 1, 2, \ldots, N\}$, to be disseminated from the RSU to the vehicles in the AoI and that each packet contains $Q$ symbols. A single packet $X_C$ is generated by combining the $N$ packets with the STNC method in the following manner:

$$X_C^i(t) = \sum_{n=1}^{N} X_n^i \alpha_n(t), \quad i = 1, 2, \ldots, Q \tag{1}$$

where $X_C^i$ and $X_n^i$ are the $i$th symbol of packets $X_C$ and $X_n$, respectively, and $\alpha_n(t)$ is the coding coefficient in the form of a complex-valued signature waveform to protect $X_n$ against the interference from other symbols. The cross-correlation between the coding factor is $\rho_{mn} = \langle \alpha_m(t), \alpha_n(t) \rangle$, where $\langle f(t), g(t) \rangle \triangleq (1/T_s) \int_0^{T_s} f(t) g^*(t) dt$, and $\rho_{nn} = 1$. For the most investigated RLNC method, the coding coefficients are randomly generated at the intermediate nodes. Therefore, the coding factors should be transmitted along with the corresponding coded packet, which results in high system overhead. However, in the adopted STNC method, the coding factors remain the same for each intermediate node and, thus, can be broadcast only once from the original data source to the end receivers. Therefore, compared with the RLNC method, the system overhead gets significantly reduced in the STNC method. Moreover, with STNC, the signal can be detected by a simple matched filtering method considering the correlation property among coding coefficients.

## IV. Proposed Data Dissemination Strategy

### A. Proposed Scheduling Framework

The scheduling by the CS is periodically performed, and the interval between two successive scheduling intervals is denoted as a data dissemination cycle. The proposed scheduling framework for data dissemination is shown in Fig. 2. As shown in Fig. 2, a data dissemination cycle is divided into the following three phases.

- **Relay Selection Phase** $T_1$**:** The CS makes the scheduling decision, i.e., selecting suitable relay nodes for the transmission frame in the relay transmission phase. There are $R$ transmission frames, i.e., $\{t_1, t_2, \ldots, t_R\}$ included in the relay transmission phase. The CS should generate the selected relay node set $\Omega_r$ for each transmission frame $t_r$, $r = 1, 2, \ldots, R$.
- **Relay Transmission Phase** $T_2$**:** All nodes including vehicles and RSUs transmit the data according to the scheduling results given in the relay selection phase. According to the transmission frame order from $t_1$ to $t_R$, nodes in set $\Omega_1$ relay data first, and nodes in set $\Omega_R$ relay data last. The duration of a transmission frame is denoted as $\ell$.
- **Feedback Phase** $T_3$**:** Each vehicle updates its current velocity, position, and decoding status to its connected RSU for the scheduling to the next data dissemination cycle.

Note that the frame number $R$ should be carefully set. It should be not too small for avoiding the frequent signaling exchange among RSUs and vehicles and not too large for catching the real state of the mobile vehicle network. Further description about the three phases will be given as follows.

*1) Relay Selection Phase:* When the CS completes the scheduling determination, it then sends the scheduling results to the RSUs involved in the AoI. Each RSU then announces the results to the vehicles in its communication range through the control channel. The time cost of the relay selection phase is assumed to be $\alpha$. The relay selection scheme will be presented in the following subsection. For the first data dissemination cycle, the relay selection is based on the initial data decoding status, i.e., no vehicles have received any data. While for the later data dissemination cycle, the relay selection is based on the decoding status fed back by the vehicles at the end of the former cycle. Since the RSU is the original source, the proposed relay selection scheme should guarantee that RSUs are the selected nodes for the first transmission frame $t_1$ in the first data dissemination cycle.

*2) Relay Transmission Phase:* If a node is selected as a relay for the transmission frame $t_r$, then it relays the data that have been correctly decoded to its neighbors with STNC. We assume that $R_k^r (R_k^r \in \{\mathbf{RSU} \cup \mathbf{U}\})$ is the selected relay node that is adjacent to $U_k$ in the transmission frame $t_r$, then the received signal at $U_k$ is

$$Y_k^r(t) = \sqrt{P_k^r} \sqrt{L_k^r} h_k^r X_C^{rk}(t) + \omega_k^r(t) \tag{2}$$

where $P_k^r$ denotes the transmit power at $R_k^r$; $L_k^r$ and $h_k^r$ denote the large- and small-scale fading coefficients of the channel between $U_k$ and $R_k^r$ in the transmission frame $t_r$, respectively; $\omega_k^r(t)$ is the noise at the receiver; and the data $X_C^{rk}(t) = \sum_{n=1}^{N} X_n \alpha_n(t) \beta_{rkn}^{t_{r-1}}$ is the coded packet with the STNC method at $R_k^r$, where $\beta_{rkn}^{t_{r-1}} = \{0, 1\}$ stands for the decoding state of packet $X_n$ at $R_k^r$ at the end of the former transmission frame $t_{r-1}$. $\beta_{rkn}^{t_{r-1}} = 1$ means successful decoding, whereas $\beta_{rkn}^{t_{r-1}} = 0$ means the opposite. If $R_k^r$ is an RSU, we have $\beta_{rkn}^{t_{r-1}} \equiv 1$. Furthermore, we assume that the channel coefficient $h_k^r$ is independent and identically distributed complex Gaussian with mean zero and variance $\sigma_h^2$, i.e., $h_k^r \sim \mathcal{CN}(0, \sigma_h^2)$. The noise $\omega_k^r(t)$ is also Gaussian with mean zero and variance $N_0$.

*3) Feedback Phase:* To eliminate the transmission collision problem in the feedback phase, each vehicle is allocated with a dedicated subchannel in the control channel band and a feedback frame to update the information. Specifically, assuming that there are $B$ resource blocks (RBs) in the control channel, the $k$th vehicle node $U_k$ then adopts the $b(= \bmod (k, B) + 1)$th, $b = 1, 2, \ldots, B$ RB and the $e(= \lceil k/B \rceil)$th, $e = 1, 2, \ldots, E$ transmission frame for the feedback information. The duration $\xi$ should be set over $E\ell(= \lceil K/B \rceil \ell)$ to ensure that all the vehicles have transmission opportunities in the feedback phase.

Moreover, when a vehicle switches from one CS control range to another CS control range during one dissemination cycle, the new CS then would hear the feedback information from the vehicle, whereas the old CS would not hear the feedback information. Under this condition, the old CS will delete the registers of those vehicles and the deleted vehicles will register to the new CS.

*4) Signal Detection:* In this paper, we adopt the matched filtering and maximal-ratio combining (MRC) methods [24] for the signal detection. For the vehicle $U_k$ to decode the packet $X_n$ from the received signal sent by $R_k^r$ within the transmission frame $t_r$, it first applies a bank of matched filters to the signals using signature waveforms, i.e.,

$$\begin{aligned} Y_{kn}^r &= \langle Y_k^r(t), \alpha_m(t) \rangle \\ &= \sqrt{P_k^r}\sqrt{L_k^r} h_k^r \sum_{n=1}^{N} X_n \beta_{rkn}^{t_{r-1}} \rho_{mn} + \omega_{km}^r. \end{aligned} \tag{3}$$

Then, it forms an $N \times 1$ vector comprised of $Y_{kn}^r$ as

$$\mathbf{Y}_k^r = \sqrt{P_k^r}\sqrt{L_k^r} h_k^r \mathbf{R}\mathbf{B}_{rk}^{t_{r-1}} \mathbf{X} + \mathbf{w}_k^r \tag{4}$$

where $\mathbf{Y}_k^r = [Y_{k1}^r, Y_{k2}^r, \ldots, Y_{kN}^r]^{\mathcal{T}}$, $\mathbf{B}_{rk}^{t_{r-1}} = \mathrm{diag}\{\beta_{rk1}^{t_{r-1}}, \beta_{rk2}^{t_{r-1}}, \ldots, \beta_{rkN}^{t_{r-1}}\}$, $\mathbf{w}_k^r = [\omega_{k1}^r, \omega_{k2}^r, \ldots, \omega_{kN}^r]^{\mathcal{T}} \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{R})$, and

$$\mathbf{R} = \begin{bmatrix} 1 & \rho_{12} & \ldots & \rho_{1N} \\ \rho_{21} & 1 & \ldots & \rho_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{N1} & \rho_{N2} & \ldots & 1 \end{bmatrix}. \tag{5}$$

The signal vector $\mathbf{Y}_k^r$ is then decorrelated to obtain

$$\tilde{\mathbf{Y}}_k^r = \mathbf{R}^{-1}\mathbf{Y}_k^r = \sqrt{P_k^r}\sqrt{L_k^r} h_k^r \mathbf{B}_{rk}^{t_{r-1}} \mathbf{X} + \tilde{\mathbf{w}}_k^r \tag{6}$$

where $\tilde{\mathbf{w}}_k^r \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{R}^{-1})$. The detected signal $X_n$ at $U_k$, i.e., the $n$th element of the vector $\tilde{\mathbf{Y}}_k^r$ is

$$\tilde{Y}_{kn}^r = \sqrt{P_k^r}\sqrt{L_k^r} h_k^r \beta_{rkn}^{t_{r-1}} X_n + \tilde{\omega}_{kn}^r \tag{7}$$

where $\tilde{\omega}_{kn}^r \sim \mathcal{CN}(0, N_0\varepsilon_n)$ with $\varepsilon_n$ being the $n$th diagonal element of the matrix $\mathbf{R}^{-1}$ associated with the packet $X_n$.

Since $U_k$ can receive $r$ same relaying signals from the transmission frame $t_1$ to $t_r$, it can further detect the desired packet $X_n$ by using an MRC detector. The final detected packet $X_n$ is then given by

$$\hat{Y}_{kn}^r \triangleq a_{kn}^r X_n + \hat{\omega}_{kn}^r \tag{8}$$

where

$$a_{kn}^r = \sum_{i=1}^{r} \frac{P_k^i L_k^i \left\| h_k^i \right\|^2 \beta_{ikn}^{t_{i-1}}}{N_0 \varepsilon_n} \tag{9}$$

and $\hat{\omega}_{kn}^r \sim \mathcal{CN}(0, a_{kn}^r)$. Note that when the relay nodes in all the $R$ frames fail to decode $X_n$, i.e., $\beta_{ikn}^{t_{i-1}} = 0$, $U_k$ then cannot correctly decode $X_n$. However, the chance happening is very small and can be negligible.

### *B. Proposed Relay Selection Strategy*

The aim of the relay selection strategy is to assign the transmission frame to the node set with the maximum dissemination utility. When the packet decoding state at a vehicle changes from failure to success after receiving the forwarding data from a relay, we then consider the relay as useful. The proposed scheme generates the selected node set $\Omega_1$ first and $\Omega_R$ last according to the transmission frame order. For each transmission frame $t_r$ for $r = 1, 2, \ldots, R$, the required information to run the relay selection includes the predicted decoding status after the transmission frame $t_{r-1}$ and vehicle velocity and position. Specifically, we denote the decoding status of packet $X_n$ at node $R_x$ ($R_x \in \{\mathbf{RSU} \cup \mathbf{U}\}$) predicted after $t_{r-1}$ as $\tilde{\beta}_{R_x n}^{t_{r-1}}$. For the first transmission frame, i.e., $r = 1$, $\tilde{\beta}_{R_x n}^{t_0}$ is equal to the initial decoding status at the start of the dissemination cycle. For the frame $t_r$ for $r = 2, 3, \ldots, R$, $\tilde{\beta}_{R_x n}^{t_{r-1}}$ is predicted based on the relay selection result $\Omega_{r-1}$. Note that if $R_x$ is an RSU, we have $\tilde{\beta}_{R_x n}^{t_{r-1}} \equiv 1$. Moreover, if $R_x$ is a vehicle, for the first dissemination cycle $\tilde{\beta}_{R_x n}^{t_0} = 0$ and for the later dissemination cycle $\tilde{\beta}_{R_x n}^{t_0}$ is equal to the decoding status fed back by vehicles at the end of the corresponding former dissemination cycle.

Assume that $R_x (R_x \in \{\mathbf{RSU} \cup \mathbf{U}\})$ is the candidate relay node. The general relay selection scheme for each transmission frame $t_r$ for $r = 1, 2, \ldots, R$ is carried out as follows.

*Step 1—SNR Calculation:* To obtain the node utility, we first calculate the signal-to-noise ratio (SNR) for packet decoding. With MRC, the SNR at $U_k$ to decode the packet $X_n$ after data relaying from $R_x$ is

$$\gamma_{kn}^{t_r, R_x} = \sum_{i=1}^{r-1} \frac{P_k^i L_k^i \left\| h_k^i \right\|^2}{N_0 \varepsilon_n} \tilde{\beta}_{ikn}^{t_{i-1}} + \frac{P_{R_x} L_{R_x k}^{t_r} \left\| h_{R_x k}^{t_r} \right\|^2}{N_0 \varepsilon_n} \tilde{\beta}_{R_x n}^{t_{r-1}} \tag{10}$$

where $P_{R_x}$ is the transmit power of $R_x$, and $L_{R_x k}^{t_r}$ is the path loss between $R_x$ and $U_k$ when $R_x$ disseminates data in frame $t_r$. Furthermore, $L_{R_x k}^{t_r}$ is dependent on the distance between $R_x$ and $U_k$ and is given by $L_{R_x k}^{t_r} = f_L(d_{R_x k}^{t_r})$, where $f_L$ is the distance dependent path loss, and $d_{R_x k}^{t_r} = \sqrt{(X_{R_x}^{t_r} - X_k^{t_r})^2 + (Y_{R_x}^{t_r} - Y_k^{t_r})^2}$ is the distance between $R_x$ and $U_k$ in the frame $t_r$. $(X_{R_x}^{t_r}, Y_{R_x}^{t_r})$ and $(X_{U_k}^{t_r}, Y_{U_k}^{t_r})$ denote the position of $R_x$ and $U_k$ in the frame $t_r$ via $XY$ plane, respectively. We then calculate the position of node $U \in \{R_x, U_k\}$ by $X_U^{t_r} = X_U^{t_f} + v_U^X \cdot T_{rf}$ and $Y_U^{t_r} = Y_U^{t_f} + v_U^Y \cdot T_{rf}$, where $(X_U^{t_f}, Y_U^{t_f})$ denotes the feedback position from node $U$ at time $t_f$, $\vec{v}_U = (v_U^X, v_U^Y)$ is the corresponding feedback $XY$-velocity components of node $U$, and $T_{rf}$ is the duration between frame $t_r$ and feedback time $t_f$.

Moreover, the corresponding average SNR is formulated as

$$\bar{\gamma}_{kn}^{t_r,R_x} = E\left[\gamma_{kn}^{t_r,R_x}\right] = \sum_{i=1}^{r-1} \frac{P_k^i L_k^i \sigma_h^2}{N_0 \varepsilon_n} \tilde{\beta}_{ikn}^{t_{i-1}} + \frac{P_{R_x} L_{R_x k}^{t_r} \sigma_h^2}{N_0 \varepsilon_n} \tilde{\beta}_{R_x n}^{t_r}. \tag{11}$$

*Step 2—Utility Calculation:* After receiving the signal relayed by $R_x$ in the transmission frame $t_r$, the decoding status to decode $X_n$ at $U_k$ is given by

$$\tilde{\beta}_{kn}^{t_r,R_x} = \begin{cases} 1, & \bar{\gamma}_{kn}^{t_r,R_x} \geq \gamma_{\text{th}} \\ 0, & \bar{\gamma}_{kn}^{t_r,R_x} < \gamma_{\text{th}} \end{cases} \tag{12}$$

where $\gamma_{\text{th}}$ denotes the successful decoding threshold. Therefore, the utility of $R_x$ as a relay node for the transmission frame $t_r$ is calculated by

$$\Phi^{t_r,R_x} = \sum_{k=1, \mathrm{U}_k \in \mathcal{N}_{R_x}^r}^{K} \sum_{n=1}^{N} \varphi_{kn}^{t_r,R_x} \tag{13}$$

where $\varphi_{kn}^{t_r,R_x} = \tilde{\beta}_{kn}^{t_r,R_x} - \tilde{\beta}_{kn}^{t_{r-1}}$ is the utility of $R_x$ for $U_k$ to decode the packet $X_n$, and $\mathcal{N}_{R_x}^r$ is the neighboring node set of $R_x$ in the frame $t_r$.

*Step 3—Relay Selection Scheme Formulation:* Denote the optimally selected relay node set for the transmission frame $t_r$ as $\Omega_r = \{R_1^*, R_2^*, \ldots, R_{L_r}^*\}$. The relay selection algorithm to select the relay node set for $t_r$ is then formulated as

$$\max_{L_r, \Omega_r} \sum_{i=1}^{L_r} \Phi^{t_r,R_i^*} \tag{14}$$

$$\text{s.t.} \quad \mathcal{N}_{R_i^*}^r \cap \mathcal{N}_{R_j^*}^r = \emptyset \quad i \neq j, \quad \forall i,j = 1,2,\ldots,L_r \tag{15}$$

$$\Phi^{t_r,R_i^*} > 0, \quad \forall i = 1,2,\ldots,L_r. \tag{16}$$

Note that at the beginning of the data dissemination, only the original source, i.e., the RSU has the dissemination utility. Therefore, the relay node selected in the set $\Omega_1$ for the first data dissemination cycle will definitely be an RSU with the proposed relay selection strategy.

When the network gets dense with a large number of vehicles, the computation complexity to solve (14) will be surprisingly high. Therefore, a suboptimal relay selection scheme is proposed for practical application, as shown in Algorithm 1 in Table I. The basic idea of the suboptimal relay selection scheme is first to select the relay node $R_1^*$ with the maximum utility from the initial candidate relay set, then update the candidate relay node set by deleting the nodes that have a common neighboring node with $R_1^*$, and repeat this until the candidate relay node set is empty.

*Step 4—Decoding Status Updating:* After the relay selection procedure for the transmission frame $t_r$, the decoding status at vehicle $U_k$ is predicted and updated as

$$\tilde{\beta}_{kn}^{t_r} = \begin{cases} \tilde{\beta}_{kn}^{t_r,R_k^r}, & \text{if } U_k \in \mathcal{N}_{R_k^r}^r \text{ and } R_k^r \in \Omega_r \\ \tilde{\beta}_{kn}^{t_{r-1}}, & \text{otherwise.} \end{cases} \tag{17}$$

TABLE I
PROPOSED RELAY SELECTION SCHEME

| **Algorithm 1:** The proposed suboptimal relay selection scheme for the $r$th ($r = 1, 2, \ldots, R$) relay transmission frame |
|---|
| 1. **Initialize** the candidate relay node set $\Lambda = \{\mathbf{RSU} \cup \mathbf{U}\}$, in which all the nodes in the network are included.<br>**Initialize** the number of selected relay nodes $L_r = 0$ and the selected relay node set $\Omega_r = \varnothing$.<br>2. **While** $\Lambda \neq \varnothing$<br>3. $L_r = L_r + 1$<br>4. Select the nodes from the set $\Lambda$ with the max utility, which is denoted as $R_{L_r}^*$, i.e.,<br>$\Phi^{t_r,R_{L_r}^*} = \max_{R_x \in \Lambda} \Phi^{t_r,R_x}$<br>5. Add the node $R_{L_r}^*$ to the set $\Omega_r$, i.e.,<br>$\Omega_r \leftarrow \Omega_r \cup \left\{R_{L_r}^*\right\}$<br>6. Update the set $\Lambda$ by deleting the nodes which have common neighboring nodes with $R_{L_r}^*$, i.e.,<br>$\Lambda \leftarrow \Lambda - \left\{ \tilde{R} \middle| \mathcal{N}_{\tilde{R}}^r \cap \mathcal{N}_{R_{L_r}^*}^r \neq \emptyset \right\}$<br>7. **End While**<br>8. **Output** the result set $\Omega_r$. |

The relay selection for the next transmission frame $t_{r+1}$ is then based on $\tilde{\beta}_{kn}^{t_r}$ with the proposed relay selection strategy.

Based on the relay selection strategy, the overall procedure of the proposed data dissemination approach is shown in Fig. 3. The relay selection phase, relay transmission phase, and feedback phase are performed orderly and periodically in the data dissemination procedure. Note that if all vehicles in the AoI have already received the whole $N$ packets, i.e., $\beta_{kn}^{t_0} = 1$ for any $U_k$ and $X_n$, then there is no need for the CS to run the relay selection process, and the overall data dissemination process gets to the end.

## V. Simulations and Discussions

Here, we evaluate the performance of the proposed data dissemination strategy by simulations. We compare the proposed strategy with the random-access method CodeOn-Basic [13], which is based on RLNC and the purely broadcasting method with RSU. Compared with the symbol-level CodeOn method, the CodeOn-Basic is packet level. Once the error symbols are detected, the whole packet will be discarded although some symbols have been right decoded. For the CodeOn-Basic method, each node $U_k$ exchanges the number of right-decoded packets $r_k$ with their one-hop neighbors and then calculate its data rebroadcasting utility as $Z_k = (1|\mathcal{N}_{U_k}|)(\sum_{U_j \in \mathcal{N}_{U_k}} r_k - r_j)$. Each node then waits for a random time before relaying the data, and the waiting time for $U_k$ is denoted as $t_k = (1 - (Z_k/N|\mathcal{N}_{U_k}|))\Delta t_{\max} + rand(0, T_J)$, where $\Delta t_{\max}(= 2\ \text{ms})$ and $T_J(= 100\ \mu\text{s})$ in [13]. We can see that the greater the utility, the smaller the average waiting time before accessing the channel. For the purely broadcasting method, the data are only transmitted by the RSU without any NC. The overhead cost and the time cost for computing and data decoding in the proposed and CodeOn-Basic are negligible in the simulations due to the difficulty for recording. Similar with the proposed strategy, we assume that the overhead transmission is also error free in CodeOn-Basic. The performance of payload is the only concern in the comparisons among the proposed strategy, CodeOn-Basic, and the purely broadcasting method.

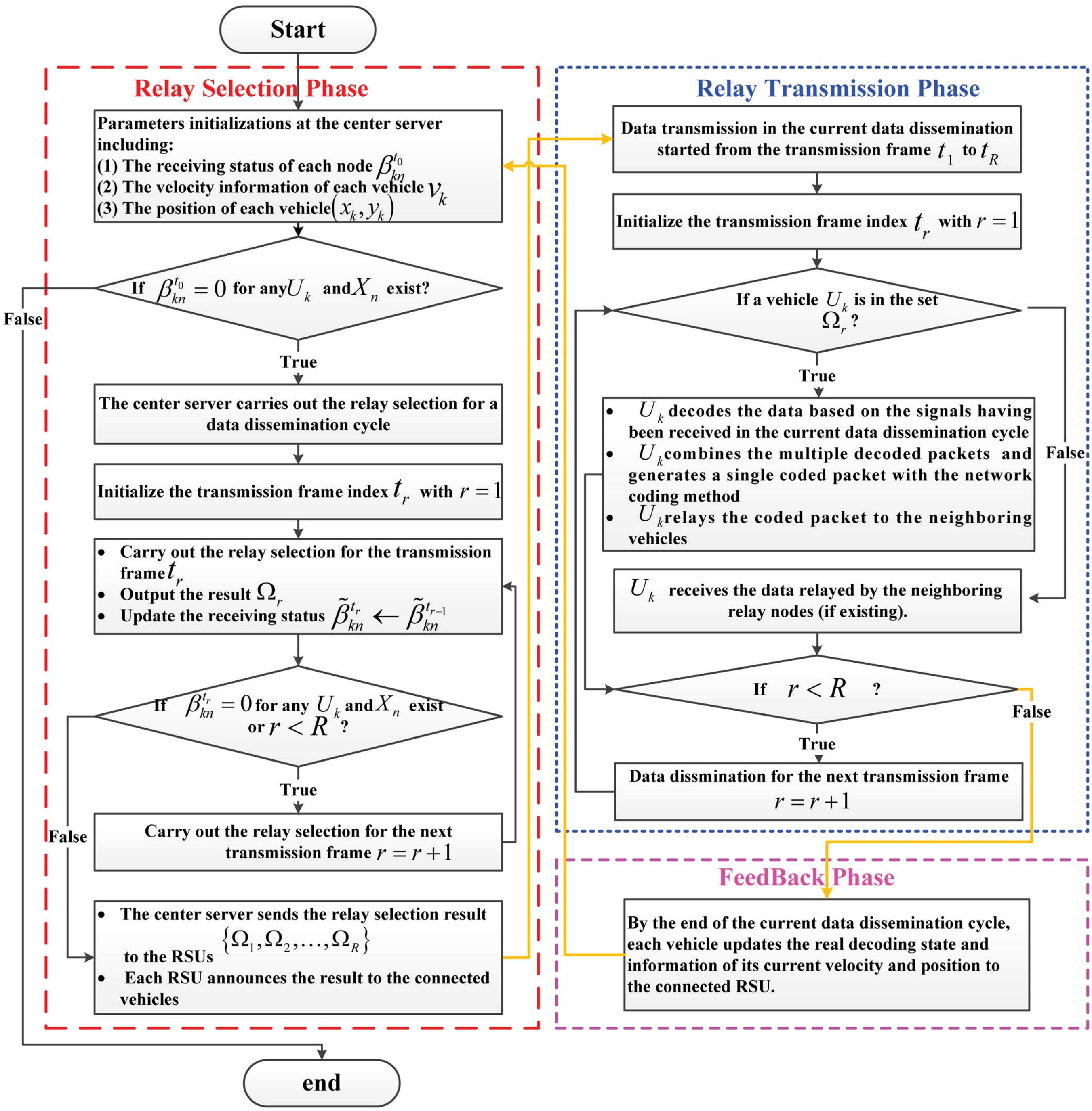


Fig. 3. Overall diagram of the proposed data dissemination strategy.

We consider both highway and urban scenarios in the simulations, as shown in Fig. 4. The AoI in the highway scenario consists of a bidirectional four-lane highway with a length of 6 km, whereas the AoI in the urban scenario is 4 km × 4 km, as shown in Fig. 4. To evaluate the impact of topology and traffic density, we simulate sparse and dense traffic for both scenarios. The vehicles are uniformly distributed in the AoI. When a vehicle moves out of the area, it will be randomly generated in the map. The simulation parameter settings are listed in Table II. We set the decoding SNR threshold $\gamma_{\mathrm{th}}(= 3\ \mathrm{dB})$ to ensure that the bit error rate is not over $10^{-2}$, which is investigated in [30]. The packet with $Q(= 48)$ binary phase-shift keying modulated

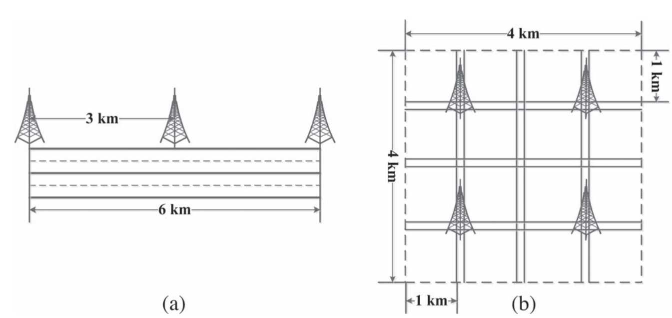


Fig. 4. (a) Highway scenario. (b) Urban scenario.

TABLE II
SIMULATION PARAMETER SETTINGS

| Parameters | Settings |
|---|---|
| Time duration relay selection phase $\alpha$ | $10ms$ |
| Time duration feedback phase $\xi$ | $10ms$ |
| Transmission frame duration $\ell$ | $1ms$ |
| Maximum number of relay transmission frame $R$ | 100 |
| Size of original packets $N$ | 10 |
| Size of a original packet $Q$ | 48 |
| Modulation mode | BPSK |
| Transmission Power at RSU | $40dBm$ |
| Transmission Power at vehicles | $20dBm$ |
| Decoding SNR threshold $\gamma_{th}$ | $3dB$ [30] |
| Path loss model | $L = 40log_{10}d + 20log_{10}f - 20log_{10}h_th_r$ [31]<br>Carrier frequency $f = 5.9GHz$<br>RSU height $h_t = 8m$<br>Vehicle height $h_r = 1m$ |
| Fading model | Rayleigh fading channel with zero mean and unit variance, i.e.$\mathcal{CN}$ (0,1) |
| Highway scenario | Sparse highway with 100 vehicles<br>Dense highway with 300 vehilces |
| Urban scenario | Sparse urban with 160 vehicles<br>Dense urban with 400 vehilces |
| Vehicle velocity | Randomly drown from [20 30]$m/s$ with a maximum acceleration of $0.5m/s^2$ |

symbols then can be regarded as correctly decoded when the SNR is over $\gamma_{\rm th}$. To indicate the interference impact on the signal detection due to the nonorthogonal code in the STNC, we consider unique cross-correlations $\rho_{mn} = \rho$ for all $n \neq m$. Accordingly, we have $\varepsilon_n = (1 + (N-2)\rho/(1-\rho)(1+(N-1)\rho)) \triangleq \varepsilon$ [24].

In the simulation, the delay performance of each strategy is evaluated from two aspects: 1) downloading progress, which is the average downloading percentage of the packet change over the elapsed time (averaged upon each vehicle); and 2) average downloading delay, which is the average elapsed time from downloading start to full completion. We first illustrate the downloading progress in the highway and urban scenarios in Fig. 5 for both sparse and dense scenarios in Fig. 5(a)–(d), respectively, whereas the average delay performances in the highway and urban scenarios are shown in Figs. 6 and 7, respectively. We then demonstrate the observations as follows.

### A. Strategy Comparison

We can see that the proposed strategy in this paper significantly outperforms both CodeOn-Basic and only broadcasting from the RSU. For the *RSU only*, each vehicle can receive the disseminated packets successfully only when its position is close to the RSU with a good channel state. Compared with *RSU only*, both CodeOn-Basic and the proposed strategy perform better than it, which proves the advantages of the NC and cooperation among vehicles. The advantage of the proposed strategy over the CodeOn-Basic benefits from the noncollision transmission and space–time diversity in STNC. For the signal detection in STNC, each vehicle does not discard the received signals relayed by its neighborhood even if it cannot decode the original packets with them. Instead, it combines the new reached signal and the signals received before to detect the original packets. The signals are generally relayed by different nodes with a different transmission frame. Therefore, each vehicle profits from the great space–time diversity in the signal detection with STNC. However, in the CodeOn-Basic with RLNC, the receiver should successfully collect $N$ independent coded packets before decoding the original $N$ packets, which enlarges the dissemination delay. Moreover, since each coded packet is generated by random coding coefficients, the receiver cannot apply the MRC method as STNC to improve the successful decoding probability. Therefore, the proposed strategy easily outperforms the CodeOn-Basic.

### B. Sparse VS Dense

Compare Fig. 5(a) with Fig. 5(b) or (c) with Fig. 5(d), we can see that both CodeOn-basic and *RSU only* perform worse in the dense network than sparse network. For *RSU only*, the reason is that more nodes are distributed in the edge of the RSU range under the dense condition compared with the sparse scenario. It then takes more time for them moving close to the RSU to receive the disseminated data with high successful probability. For CodeOn-Basic, the worse performance is due to the transmission collision problem. In the dense network, the decoding status of each vehicle is generally close to that of its neighborhood. That is to say, the utility of data relaying by each vehicle is almost the same with that of its neighborhood. It directly results the waiting time before data relaying at each vehicle and its neighborhood is very close, which further leads to the transmission collision. Therefore, the dissemination delay gets enlarged in the dense network with CodeOn-Basic. However, for the proposed strategy, it performs contrary with both CodeOn-Basic and *RSU only*. It is because in the dense network, it can select more suitable relay nodes for data relaying. The space diversity gets further exploited under the dense condition. The data dissemination delay performance thus gets significantly improved with the proposed strategy. Moreover, the transmission collision gets avoided in the proposed relay selection scheme. Therefore, the gap between the proposed strategy and CodeOn-Basic and *RSU only* is increased in the dense network.

### C. Orthogonal VS Nonorthogonal STNC

We note that when the coding coefficients in the STNC are not orthogonal, i.e., $\rho \neq 0$, the performance of the proposed strategy deteriorates with the increasing correlation factor. In the signal detection process of STNC, we adopt the matched filtering method whitening the unwanted signals as noise. Therefore, when the correlation factor $\rho$ between the coding coefficients is bigger, the whitened noise is more. The effective SNR for decoding signal thus is decreased with increasing $\rho$. The dissemination delay performance then gets negatively affected with increasing $\rho$. However, even with a high correlation factor, i.e., $\rho = 0.9$, the proposed strategy still outperforms the CodeOn-Basic and *RSU only*, which further demonstrates the effectiveness and high efficiency of the proposed strategy.

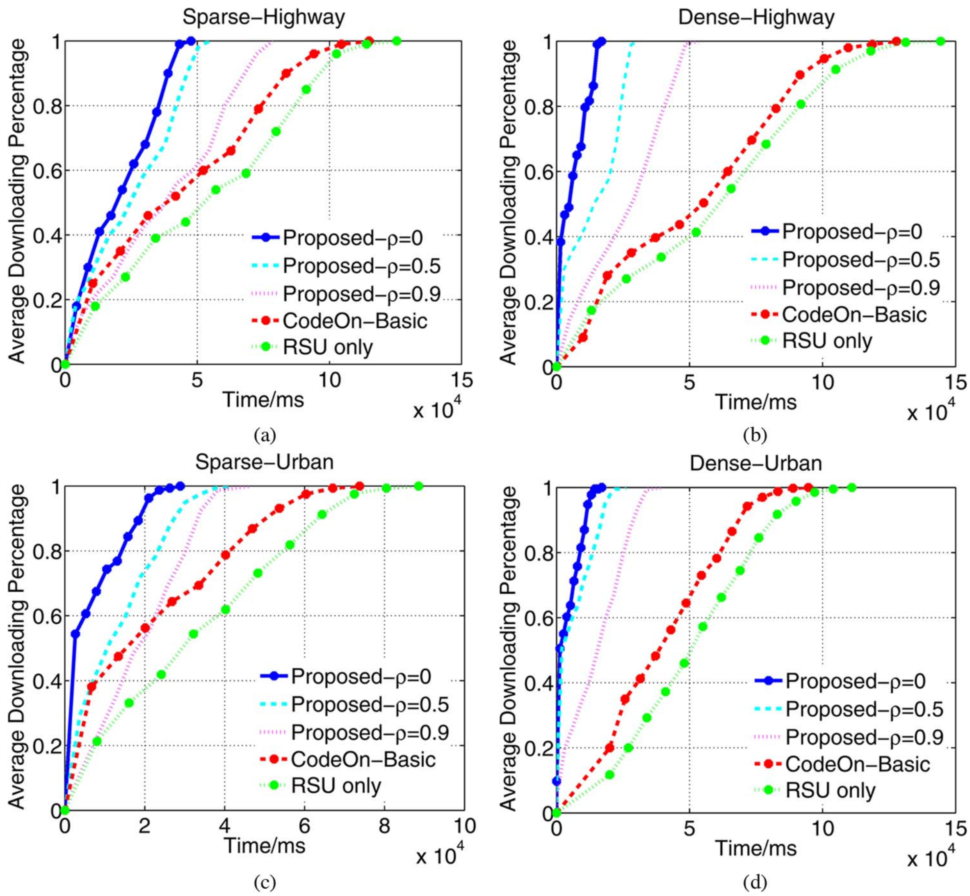


Fig. 5. Data dissemination progress in the urban scenario. (a) Sparse highway. (b) Dense highway. (c) Sparse urban. (d) Dense urban.

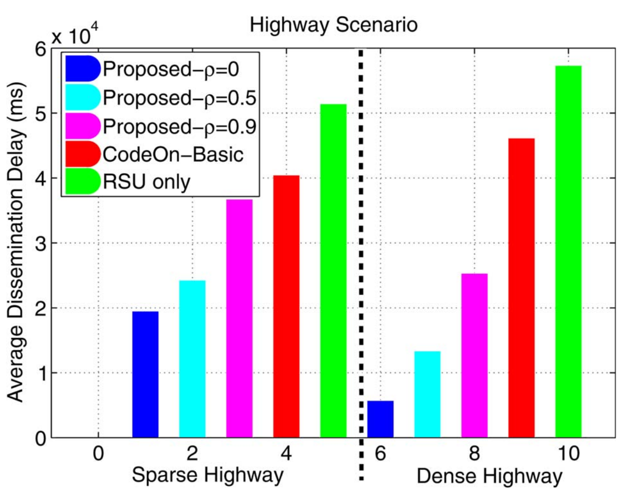


Fig. 6. Average downloading delay performance in the highway scenario.

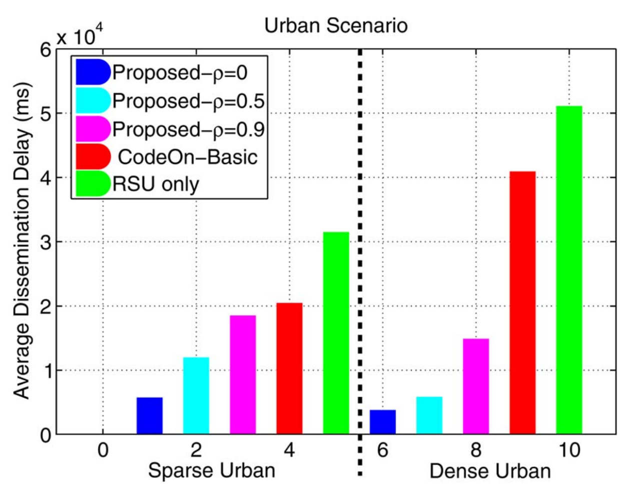


Fig. 7. Average downloading delay performance in the urban scenario.

## VI. Conclusion

In this paper, we have proposed a novel data dissemination strategy for VANETs from a scheduling perspective to avoid the collision problem. A general framework has been presented to carry out the scheduling strategy. The challenge of allowing the nodes with maximum transmission utility relay data first has been addressed by a judiciously designed relay selection strategy. In addition, a simple NC method, namely, STNC with low signal detection complexity and space–time diversity gain, is adopted in the proposed strategy. Simulation results showed that, compared with the CodeOn-Basic with RLNC and the noncooperative transmission strategy, our proposed strategy performs better in terms of the dissemination delay. Moreover, benefitting from the space–time diversity gain of STNC, the proposed strategy performs even better in the dense network than in the sparse scenario, which is in sharp contrary to the CodeOn-Basic random-access strategy.

## REFERENCES


[1] J. Zhang, F. Y. Wang, K. Wang, W. H. Lin, X. Xu, and C. Chen, "Data-driven intelligent transportation systems: A survey," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 1624–1639, Dec. 2011.

[2] L. Yang and F. Wang, "Driving into intelligent spaces with pervasive computing and communications," *IEEE Intell. Syst.*, vol. 22, no. 1, pp. 12–15, Jan./Feb. 2007.

[3] X. Cheng, Q. Yao, M. Wen, C.-X. Wang, L. Song, and B. Jiao, "Wideband channel modeling and ICI cancellation for vehicle-to-vehicle communication systems," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 9, pp. 434–448, Sep. 2013.

[4] X. Cheng, C.-X. Wang, B. Ai, and H. Aggoune, "Envelope level crossing rate and average fade duration of non-isotropic vehicle-to-vehicle Ricean fading channels," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 1, pp. 62–72, Feb. 2014.

[5] C. X. Wang, X. Cheng, and D. Laurenson, "Vehicle-to-vehicle channel modeling and measurements: Recent advances and future challenges," *IEEE Commun. Mag.*, vol. 47, no. 11, pp. 96–103, Nov. 2009.

[6] X. Cheng, C. X. Wang, D. Laurenson, S. Salous, and A. Vasilakos, "An adaptive geometry-based stochastic model for non-isotropic MIMO mobile-to-mobile channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 9, pp. 4824–4835, Sep. 2009.

[7] X. Cheng, Q. Yao, C. X. Wang, B. Ai, G. L. Stuber, D. Yuan, and B. Jiao, "An improved parameter computation method for a MIMO V2V Rayleigh fading channel simulator under non-isotropic scattering environments," *IEEE Commun. Lett.*, vol. 17, no. 2, pp. 265–268, Feb. 2013.

[8] X. Cheng, C.-X. Wang, and D. I. Laurenson, "A geometry-based stochastic model for wideband MIMO mobile-to-mobile channels," in *Proc. IEEE GLOBECOM*, Honolulu, HI, USA, Dec. 2009, pp. 1–6.

[9] X. Cheng, C.-X. Wang, D. I. Laurenson, H. H. Chen, and A. V. Vasilakos, "Space–time–frequency characterization of non-isotropic MIMO mobile-to-mobile multicarrier Ricean fading channels," in *Proc. IWCMC*, Crete Island, Greece, Aug. 2008, pp. 994–999.

[10] A. Nandan, S. Das, G. Pau, M. Gerla, and M. Y. Sanadidi, "Co-operative downloading in vehicular ad-hoc wireless networks," in *Proc. WONS*, St. Moritz, Switzerland, Jan. 2005, pp. 32–41.

[11] A. Nandan, S. Tewari, S. Das, M. Gerla, and L. Kleinrock, "AdTorrent: Delivering location cognizant advertisements to car networks," in *Proc. WONS*, Les Menuires, France, Jan. 2006, pp. 203–212.

[12] U. Lee, J. S. Park, J. Yeh, G. Pau, and M. Gerla, "Code torrent: Content distribution using network coding in VANET," in *Proc. MobiShare*, Los Angeles, CA, USA, Sep. 2006, pp. 1–5.

[13] M. Li, Z. Yang, and W. Lou, "CodeOn: Cooperative popular content distribution for vehicular networks using symbol level network coding," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 223–235, Jan. 2011.

[14] T. Yu, C. Yi, and S. Tsao, "Rank-based network coding for content distribution in vehicular networks," *IEEE Wireless Commun. Lett.*, vol. 1, no. 4, pp. 368–371, Aug. 2012.

[15] M. Gerlay, R. G. Cascella, Z. Caoy, B. Crispo, and R. Battiti, "An efficient weak secrecy scheme for network coding data dissemination in VANET," in *Proc. IEEE PIMRC*, Cannes, France, Sep. 2008, pp. 1–5.

[16] M. Sardari, F. Hendessi, and F. Fekri, "DMRC: Dissemination of multimedia in vehicular networks using rateless codes," in *Proc. IEEE INFOCOM Workshops*, Rio De Janeiro, Brazil, Apr. 2009, pp. 19–25.

[17] C. Stefanovic, D. Vukobratovic, F. Chiti, L. Niccolai, V. Crnojevic, and R. Fantacci, "Urban infrastructure-to-vehicle traffic data dissemination using UEP rateless codes," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 94–102, Jan. 2011.

[18] V. Palma, E. Mammi, A. M. Vegni, and A. Neri, "A fountain codes-based data dissemination technique in vehicular ad-hoc networks," in *Proc. ITST*, St. Petersburg, Russia, Aug. 2011, pp. 750–755.

[19] J. Zhang, Q. Zhang, and W. Jia, "VC-MAC: A cooperative MAC protocol in vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 58, no. 3, pp. 1561–1571, Mar. 2009.

[20] N. Cenerario, T. Delot, and S. Ilarri, "A content-based dissemination protocol for VANETs: Exploiting the encounter probability," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 3, pp. 771–782, Sep. 2011.

[21] F. J. Ros, P. M. Ruiz, and I. Stojmenovic, "Acknowledgment-based broadcast protocol for reliable and efficient data dissemination in vehicular ad hoc networks," *IEEE Trans. Mobile Comput.*, vol. 11, no. 1, pp. 33–46, Jan. 2012.

[22] D. Wu, Y. Zhang, L. Bao, and A. C. Regan, "Location-based crowd sourcing for vehicular communication in hybrid networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 2, pp. 837–846, Jun. 2013.

[23] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments*, IEEE Std. 802.11p-2010, Jul. 2010, pp. 1–51.

[24] H. Q. Lai and K. J. R. Liu, "Space–time network coding," *IEEE Trans. Signal Process.*, vol. 59, no. 4, pp. 1706–1718, Apr. 2011.

[25] H. Tracey, M. Medard, R. Koetter, D. R. Karger, M. Effros, S. Jun, and B. Leong, "A random linear network coding approach to multicast," *IEEE Trans. Inf. Theory*, vol. 52, no. 10, pp. 4413–4430, Oct. 2006.

[26] H. D. T. Nguyen, L. N. Tran, and E. K. Hong, "On transmission efficiency for wireless broadcast using network coding and fountain codes," *IEEE Commun. Lett.*, vol. 15, no. 5, pp. 569–571, May 2011.

[27] D. Sejdinovic, D. Vukobratovic, A. Doufexi, V. Senk, and R. J. Piechocki, "Expanding window fountain codes for unequal error protection," *IEEE Trans. Commun.*, vol. 57, no. 9, pp. 2510–2516, Sep. 2009.

[28] C. Fragouli, J. Widmer, and J. Y. Le Boudec, "Efficient broadcasting using network coding," *IEEE/ACM Trans. Netw.*, vol. 16, no. 2, pp. 450–463, Apr. 2008.

[29] N. Dong, T. Tran, N. Thinh, and B. Bose, "Wireless broadcast using network coding," *IEEE Trans. Veh. Technol.*, vol. 58, no. 2, pp. 914–925, Feb. 2009.

[30] W. P. Siriwongpairat, T. Himsoon, W. Su, and J. R. K. Liu, "Optimum threshold-selection relaying for decode-and-forward cooperation protocol," in *Proc. IEEE WCNC*, Apr. 2006, pp. 1015–1020.

[31] R. A. Santos, V. Rangel, L. Villaseñor, and A. Edwards, "Wireless propagation characteristics for vehicular ad hoc networks in motorway environments," *Rev. Investigacióny Tecnol.*, vol. X, no. 4, pp. 295–302, 2009.

[32] X. Shen, X. Cheng, R. Zhang, B. Jiao, and Y. Yang, "Distributed congestion control approaches for the IEEE 802.11p vehicular networks," *IEEE Intell. Transp. Syst. Mag.*, vol. 5, no. 4, pp. 50–61, Winter 2013.



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