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RESEARCH

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Fuzzy logic-based integrity-oriented file transfer for highway vehicular communications

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Abstract
Effective file transfer is fundamental to many applications in highway Vehicular Ad Hoc Networks (VANETs), e.g., social network applications, advertisement distributions, road traffic report, etc. However, due to the sparse development of roadside units (or access points) and the limited connection time between fast-moving vehicles, file transfer is susceptible to frequent interruptions, and accordingly resulting in incomplete file transfers. The incomplete file transfer leads to not only poor user performance with application playback failures, but also a colossal waste of bandwidth. To tackle this issue, in this paper, we consider a bi-directional highway vehicular network scenario where request vehicle and source vehicle are in the opposite direction, and propose a fuzzy logic-based cooperative file transfer scheme (FL-CFT). With the proposed scheme, the request file can be transferred completely from the source vehicle to request vehicle through multiple relay cluster members. As for the selection of relays, in general, finding an optimal relay subject to multiple constrains is an NP-complete problem that cannot be exactly solved in polynomial time. Accordingly, a fuzzy logic approach is utilized to optimally selects relays to help transfer the file and ensure the file integrity, which considers the relative velocity, distance, and predicted connection time among vehicles. The proposed scheme is self-organized and fully distributed, which does not require any assistance from roadside units (or access points). Simulation results show that FL-CFT outperforms the state-of-the-art file transfer schemes in file integrity on highway VANETs.

Keywords: VANETs, Fuzzy logic, Cooperative file transfer, Connection time prediction, Cluster

1 Introduction

An important application of vehicular ad hoc networks (VANETs) is to provide media-rich entertainment, such as video streaming, social communications and multimedia advertisements, and traffic-engaged service applications, such as road reports, navigation, etc., to travelers on the road to enhance their road safety, comfort, and convenience [1, 2]. Under such applications lays the fundamental requirements of transmitting data files efficiently and reliably to fast-moving vehicles using either vehicular-to-vehicle (V2V) communications or vehicle-to-infrastructure (V2I) communications. For example, a social network page may consist of multiple short video/audio files and image files.

File transmissions in VANETs have been studied in a variety of contexts in vehicular networks. Deng et al. [3] propose a Prior-Response-Incentive-Mechanism to stimulate vehicles to take part in cooperative downloading in VANETs-LTE heterogeneous networks. W. Huang et al. [4] develop a cell-based clustering scheme and a strategy of inter-cluster relay selection to construct a peer-to-peer network of scale-free property, which greatly promotes the information spread. G. Ali et al. [5] propose an enhanced CLB (ECLB) approach which reduces the number of deadline conflict requests and helps improve the overall system performance. C. Lai et al. [6] propose a secure incentive scheme to achieve fair and reliable cooperative (SIRC) downloading in highway VANETs. J. Liu et al. [7] propose a cooperative downloading method for VANET using digital fountain code (DFC) to increase the amount of downloaded data and enable the transmission to be more robust in a vehicular environment. Ota et al. [8] propose a cooperative downloading algorithm called max-throughput and min-delay cooperative downloading, in which the roadside units (RSUs) intelligently select vehicles to serve towards the minimal average delivery delay

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of file transfer. Yang et al. [9] propose a cooperation-aided max-rate first method, in which the roadside unit always selects the node with the highest data rate as the receiver to serve.

Existing file transfer schemes mainly focus on the provisioning of quality of service to users, such as minimal packet delays and maximal network throughput. The integrity of file transfer, which is crucial to the quality of experience perceived by the end users is, however, not sufficiently studied. Specifically, the vehicular communications are challenged by the short-lived connection time due to the fast node mobility. File transfers are therefore susceptible to frequent interruptions, and incomplete transmissions which cannot be finished during the vehicle's connection time. The incomplete transmissions of files lead to unusable partial files to upper-layer applications. As a result, users may tolerate a long wait, but cannot play the contents by the end. The transmissions of the partial and incomplete files would also raise a significant waste of bandwidth. Luan et al. [10] has studied the integrity-oriented content transmissions in highway vehicular networks and show that about one third of bandwidth can be wasted in the simulated scenario. However, [10] considers a simplified scenario with single-hop file transfer only; if the file that cannot be completely transmitted during the connection time will be simply discarded. In contrast to its potential theoretic value, the proposal in [10] is over-simplified and insufficient for the real-world deployment. Moreover, most existing file transfer schemes just focus on the file transfer along uni-directional road.

In this paper, we consider a bi-directional highway scenario and develop a fuzzy logic-based file transfer (FL-CFT) scheme towards high-integrity file transfer over bi-directional highway VANETs. FL-CFT adopts a cooperative approach between vehicles without the assistance of roadside units or access points. As for the selection of relays, since many factors (such as distance, relative speed, and connection time between two vehicles) have influence on the selection of relays, in general, finding an optimal relay subject to multiple constrains is an NP-complete problem that cannot be exactly solved in polynomial time [11]. Accordingly, we propose a fuzzy logic approach to optimally select relays. In FL-CFT, when the requested file cannot be completely transferred from the source vehicle to the request vehicle over a single direct V2V transmission, a cluster of neighboring vehicles is formed to collaboratively transmit the rest part of the file along multi-hop relays. To facilitate the multi-hop file transfer, a *connection time prediction model* and a *pieces-based file transfer model* are developed that can guarantee the connection time and transmission performance towards the complete file transfer. Using the above models, cluster members and intermediate relay nodes are optimally selected using a practical fuzzy logic approach.

The main contributions of the paper are threefold.

- *High-integrity file transfer*: a high-integrity file transfer scheme over the highly dynamic vehicular networks is developed. A cluster will be established to finish the file transfer and a fuzzy logic-based algorithm is developed to select the most eligible vehicle as the cooperative cluster member. The proposed scheme is fully distributed which does not require any assistance from roadside units or access points.
- *Bi-directional traffic*: we consider a bi-directional traffic case where files can be originated from an opposite driving direction efficiently. This scenario can be typical in practice, but has rarely been investigated in previous literature before.
- *Validation*: we conduct extensive simulations to verify our proposed scheme. Simulation results show that our proposed scheme can achieve high-integrity file transfer as compared to the schemes in [10] and [12].

The reminder of the paper is organized as follows: Section 2 presents the related works and Section 3 presents the models adopted in FL-CFT. Section 4 describes the details of the proposed high-integrity fuzzy logic-based cooperative file transfer scheme. Section 5 includes our experimental results, and Section 6 concludes the paper with closing remarks.

2 Related works

This section reviews the related works on cooperative file transfer schemes and some other methods exploiting the fuzzy logic system.

Gong et al. [1] propose a cloud-based mobile content distribution scheme with the assistance of roadside parked vehicles besides inter-vehicle communication. The network architecture consists of two kinds of clouds: roadside parking cloud and mobile cloud. The scheme regards the parked vehicles as RSUs. With on board wireless device and rechargeable battery, parked cars can communicate with any cars driving through them [13–17]. Moreover, [18–23] have introduced the concept of vehicle cloud which are employed for multimedia sharing and distribution. Liu et al. [24] propose a cooperative downloading strategy that can provide mobile users with varied services to access the internet via WiFi according to user-defined classes in highway scenarios. Due to the high cost associated with roadside units or access points, these schemes are not very feasible in practice. Trullols-Cruces et al. [25] propose a vehicular framework that opportunistically allows downloading packets when vehicles cross AP, works as a delay-tolerant network and benefits two cooperative mechanisms: (i) a DC-ARQ to recover packet losses due to the harsh physical conditions and (ii) a carry and forward mechanism to improve throughput and total transfer delay.

In terms of cooperative file transfer, T. Wang et al. [26] propose a cooperative approach based on coalition formation games, in which OBUs exchange their possessed pieces by broadcasting to and receiving from their neighbors. D. Yue et al. [27] study how to minimize the cost of cooperative content downloading under the hybrid VANETs and meet the requirement of the vehicular users and propose a basic meet algorithm (BMA) and a heuristic algorithm-time slot algorithm (TSA). In [28], H. Liang et al. investigate the utilization of roadside wireless local area networks (RS-WLANs) as a network infrastructure for data dissemination and present a two-level cooperative data dissemination approach. With the network-level cooperation, the resources in the RS-WLANs are used to facilitate the data dissemination services for the nomadic users. The packet-level cooperation is exploited to improve the packet transmission rate to a nomadic user. Zhou et al. [29] propose ChainCluster, a cooperative drive-thru Internet scheme. ChainCluster selects appropriate vehicles to form a linear cluster on the highway. During *content forwarding phase*, C. M. Hon et al. [30] propose a general dynamic optimal random access (DORA) algorithm to compute the optimal access policy, where time is divided into equal time slots. Each time slot consist of four parts. The first part is AP broadcasting period, the second part is transmission requesting period, the third part is AP sending ACK period, and the last part is data transmission period. After collecting the requests from all vehicles in its coverage range, the AP assigns the time slot to one of these vehicles by sending ACK to it. Therefore, how to select the eligible vehicle is challenging.

For the selection of relay nodes, R. Cai et al. [31] propose an adaptive routing protocol based on forwarding angle (ARPBFA) in VANETs, where forwarding angle and the average distance of one-hop progress are the two key parameters of the routing protocol. For fuzzy logic being suited for decision-making techniques and used for VANETs, in [32], the nodes parameters, such as residual energy, node mobility, and number of hop counts, are fed through a fuzzy inference system to compute the value of the node trust level, which can be used as a metric to construct an optimal path from source to destination. K. Ashish et al. [33] propose a heuristics for highly efficient selection of multipoint relays (MPR) in optimized link state routing (OLSR) protocol. The node parameters, such as energy, stability, and buffer occupancy, are input into fuzzy logic system to deal with the MPR selection. G. Golnoosh et al. [11] propose a reliable routing algorithm based on fuzzy-logic (RRAF) for finding a reliable reactive protocol. Their proposal combines two parameters battery power or trust of a node to discover a reliable route between the source and request vehicles.

3 System model

In this paper, we consider the scenario in which vehicles travel on a bi-directional highway with two lanes per direction. As a motivating example shown in Fig. 1, assuming that the request vehicle[1] (denoted as *R*) requests the content file and the source vehicle[2] (denoted as *S*) in the opposite direction has the the requested file, a cooperative transfer scheme is applied to complete the file transfer. We always assume that the request vehicle and the resource vehicle run in the opposite directions. To enable collaborative download, a multi-party scheme is applied, in which a file is divided into multiple pieces. Each piece is transmitted through V2V communication. The file distribution is completed when all the pieces of the file are collected by the request vehicle.

It is assumed that all vehicles are equipped with the on-board global positioning system (GPS), and all vehicles have the knowledge of their geographical locations. We just consider pure V2V communications without the assistant of roadside infrastructures, e.g., RSUs or access points (APs). This is due to the reason that the large-scale

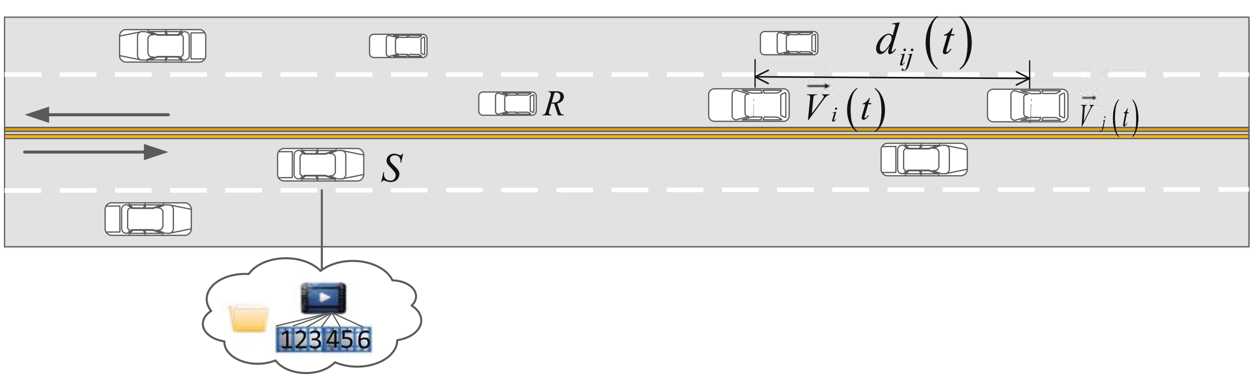

Fig. 1 Real request scenario in VANETs

deployment of RSUs or APs on highways tend to be a slow process. However, our protocol can be easily extended when the road infrastructure is available.

In this work, four models are applied to characterize the system: vehicle mobility model, connection time prediction model, vehicle-to-vehicle communication model, and pieces-based file transfer model [29]. We first present the first three models in details. For convenience, the major notations used in this paper are listed in Table 1.

3.1 Vehicle mobility model

Considering the mobility features on practical highways, we apply the free mobility model [34] to model the mobility of vehicles on highways.

The mobility features of vehicles on highway are characterized as follows: (1) the speed range of vehicle is specified by a minimum velocity and a maximum velocity. (2) We define a safety distance (SD). Namely, two adjacent vehicles on the same lane should keep the safety distance for safety purposes. If the distance between two adjacent vehicles is less than the safety distance, the rear vehicle slows down until the distance between them meets the safety distance requirement. (3) A vehicle only travels along one lane of the highway without overtaking and lane change.

Table 1 Major notations

Notation	Definition
$\mathbb{N}$	The set of vehicles on the road
$\vec{V}_i(t)$	The velocity vector of vehicle i at time t
$\vec{V}_j(t)$	The velocity vector of vehicle j at time t
$\vec{a}_i(t)$	Acceleration vector of vehicle i at time t
γ_1, γ_2	Random numbers between 0 and 1
$d_{i,j}(t_0)$	Initial distance between i and j
$d_{i,j}(t)$	Distance between i and j at time t
SD	Safety distance between two adjacent vehicles
$V_{\min}$	Minimum velocity of vehicles
$V_{\max}$	Maximum velocity of vehicles
r	Communication range of vehicles
ρ	Vehicle density
$\rho_{\max}$	Vehicle density during the traffic jam
$T_{i,j}$	Predicted connection time between i and j
$\Gamma(\mu)$	Gamma function
Ω	Average received power of received vehicle
N_r	Thermal noise power
c_k	The kth modulation rate supported by transmitter of vehicle
$E(c)$	Average transmission rate between two vehicles
s	The size of each file piece
$\mathbb{M}$	The set of file pieces
n_i	The number of pieces i exactly download from S
$C^c_{i,S}$	Communication capability between i and S
r_i^{RVF}	Related velocity factor
d_i^{DF}	Distance factor
t_i^{PCTF}	Predicted connection time factor
μ_1	Triangular membership function of input
μ_2	Triangular membership function of output
N_c	The size of cluster

In the mobility model adopted in our work, both the velocity of vehicles and the distance between two adjacent vehicles are known in priori. Figure 1 shows the case for two vehicles (i.e., i and j).

Let $\mathbb{N}$ denote the set of vehicles on the road. According to the mobility model defined, the velocities of two vehicles meet the following equations:

$$\begin{cases} \left|\vec{V}_i\,(t+\Delta t)\right| = \left|\vec{V}_i\,(t)\right| + \gamma_i\,(t) \times |\vec{a}_i(t)| \times \Delta t, \\ V_{\min} \le \left|\vec{V}_i\,(t)\right| \le V_{\max}, \\ \left|\vec{V}_j\,(t)\right| \le \left|\vec{V}_i\,(t)\right|, d_{ij}\,(t) \le \mathrm{SD}. \end{cases} \tag{1}$$

where $\vec{V}_i\,(t)$ represents the velocity vector of vehicle i ($i \in \mathbb{N}$) at time t, Δt denotes the time interval, $\gamma_i(t)$ is a random number between 0 and 1, $\vec{a}_i\,(t)$ denotes the acceleration vector of vehicle i at time t, $d_{ij}\,(t)$ denotes the distance between vehicle i and vehicle j ($j \in \mathbb{N}$) at time t. SD denotes the safety distance between two adjacent vehicles.

Accordingly, a highway mobility model can be represented approximately in terms of both time and space with these velocity equations. Let $d_{ij}(t_0)$ denote the initial distance between vehicles i and j. Let $\vec{V}(t_0)$ denote the initial velocity of vehicles, and γ_1 and γ_2 are random numbers between 0 and 1. The velocity and distance can be expressed as

$$\begin{cases} d_{ij}(t_0) = (1+\gamma_1)\times\mathrm{SD}, \\ |\vec{V}(t_0)| = V_{\min} + \gamma_2 \times (V_{\max} - V_{\min}). \end{cases} \tag{2}$$

The maximum number of vehicles that can be accommodated within the coverage of S is [30]

$$N_{\max} = \lfloor 2r \times \rho_{\max} \rfloor\,, \tag{3}$$

where $\lfloor\cdot\rfloor$ denotes the floor function, r is the communication range of S, $\rho_{\max}$ is the vehicle density during the traffic jam.

3.2 Connection time prediction model

It is assumed that the communication range of each node is r. Assume two nodes i and j are within the transmission range of each other. The position, velocity, and moving direction of node i ($i \in \mathbb{N}$) at time t are (x_i, y_i), $\vec{V}_i$ and θ_i, respectively. Similarly, the position, velocity, and moving direction of node j ($j \in \mathbb{N}$) at time t are (x_j, y_j), $\vec{V}_j$ and θ_j, respectively. The prediction model for connection time is illustrated in Fig. 2.

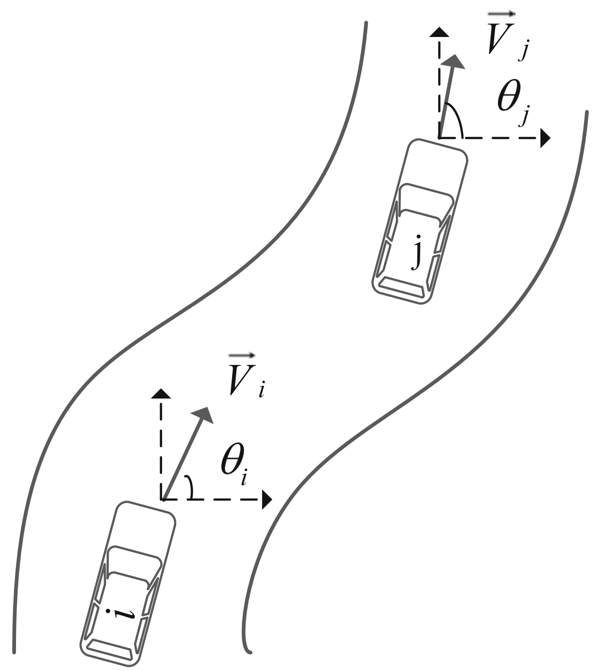

Fig. 2 Prediction model for communication connection time

For simplicity, it is assumed that the speed and direction of vehicle that is during communication period keeps unchanged in order to predict the connection time between two vehicles, let $\Delta T_{i,j}$ denote the connection time between two vehicles, and according to kinematics theory, the following formulas hold [35]:

$$\begin{cases} \Delta v_x = \mid \vec{V}_i \mid cos\theta_i - \mid \vec{V}_j \mid cos\theta_j, \\ \Delta v_y = \mid \vec{V}_i \mid sin\theta_i - \mid \vec{V}_j \mid sin\theta_j, \\ \Delta d_x = x_i - x_j, \\ \Delta d_y = y_i - y_j, \\ (\Delta d_x + \Delta v_x \times \Delta T_{i,j})^2 + (\Delta d_y + \Delta v_y \times \Delta T_{i,j})^2 = r^2, \end{cases} \tag{4}$$

Then from formula (4), ΔT_{ij} is derived as

$$\Delta T_{i,j} = \frac{-A + \sqrt{Br^2 - (\Delta v_y \Delta d_x - \Delta v_x \Delta d_y)^2}}{B}, \tag{5}$$

where A and B are two intermediate variables, which are formulated as

$$\begin{cases} A = \Delta v_x \times \Delta d_x + \Delta v_y \times \Delta d_y, \\ B = \Delta {v_x}^2 + \Delta {v_y}^2, \end{cases} \tag{6}$$

Specially, if the connection period starts at the moment when the distance between nodes i and j decreases to r and ends at the moment when their distance increases to r, i.e., communication link is established once node i is entering the communication range of node j until node i is out of the communication range of node j, the connection time can be simplified as $\Delta T'_{i,j}$ according to the following formulas:

$$\begin{cases} \Delta v_x = \mid \vec{V}_i \mid cos\theta_i - \mid \vec{V}_j \mid cos\theta_j, \\ \Delta v_y = \mid \vec{V}_i \mid sin\theta_i - \mid \vec{V}_j \mid sin\theta_j, \\ \left(\Delta v_x \times \Delta T'_{i,j}\right)^2 + \left(\Delta v_y \times \Delta T'_{i,j}\right)^2 = (2r)^2, \end{cases} \tag{7}$$

Then from formula (7), $\Delta T'_{ij}$ is derived as

$$\Delta T'_{i,j} = \frac{2r}{\sqrt{\Delta {v_x}^2 + \Delta {v_y}^2}} \tag{8}$$

Note that when $v_i = v_j$ and $\theta_i = \theta_j$, $\Delta T_{i,j}$ or $\Delta T'_{i,j}$ become ∞.

3.3 Vehicle-to-vehicle communication model

In this part, we evaluate the transmission rate of V2V communication. Duo to the fast-fading highway vehicular environment, we model the probability density function (pdf) of signal amplitude by the Nakagami(μ, Ω) distribution as [10, 29, 36]

$$f(x;\mu,\Omega) = x^{2\mu-1}\frac{2\mu^\mu}{\Gamma(\mu)\Omega^\mu}\exp\left(-\frac{\mu}{\Omega}x^2\right), \tag{9}$$

where $\Gamma(\mu)$ denotes the gamma function, which is defined as

$$\Gamma(\mu) = \int_0^\infty t^{\mu-1}e^{-t}dt, \tag{10}$$

where μ denotes the signal fading index related to the distance between two communication vehicles and the surroundings. In our work, we adopt the following reference values [36]: μ=0.74 if $d_{ij} \in [90.5, 230.7]$; μ=0.84 if $d_{ij} \in [230.7, 588]$. Ω is the average received power before envelope detection, which is defined as

$$\Omega = P_t G_t G_r \frac{h_t^2 h_r^2}{d_{ij}^\alpha L}, \tag{11}$$

where P_t denotes the transmission power. G_t and G_r denote the transmission and reception antenna gain, respectively. h_t and h_r denote the transmission and reception antenna length, respectively, L denotes the loss coefficient of the system, and α denotes the path loss exponent. With (9), we can calculate the probability density function of the signal to noise ratio (SNR) using the following formula:

$$P_r\left(\frac{\Omega}{N_r} \le x\right) = 1 - \frac{\Gamma\left(\mu, \frac{\mu}{\Omega}N_r x\right)}{\Gamma(\mu)}, \tag{12}$$

where N_r is the thermal noise power, $\Gamma\left(\mu, \frac{\mu}{\Omega}N_r x\right)$ is formulated as:

$$\Gamma\left(\mu, \frac{\mu}{\Omega}N_r x\right) = \int_{\frac{\mu}{\Omega}N_r x}^\infty e^{-x}x^{\mu-1}dx. \tag{13}$$

We assume that the transmitter of each node in vehicular environment supports K discrete modulation rates, c_k

denotes the kth modulation rate ($c_1 < c_2 < \cdots < c_k$, $1 \leq k \leq K$). Let ν_k denote the pre-set threshold, and if the current SNR meets the following condition: $\nu_k \leq \frac{\Omega}{N_r} \leq \nu_{k+1}$, the module velocity is set to c_k. In addition, we set $\nu_{K+1} = \infty$. Consequently, according to the equations mentioned previously, the transmission rate c_k is selected with the probability:

$$P_r\{C = c_k\} = \begin{cases} \frac{1}{\Gamma(\mu)}(\Gamma_k - \Gamma_{k+1}),\ 1 \leq k \leq K-1 \\ \frac{\Gamma_k}{\Gamma(\mu)},\ k = K \end{cases} \tag{14}$$

$$\Pr\{C = 0\} = 1 - \sum_{1}^{K} \Pr\{C = c_k\}, \tag{15}$$

where Γ_k and Γ_{k+1} are defined as

$$\begin{cases} \Gamma_k = \int_{\frac{\mu}{\Omega}N_r\nu_k}^{\infty} y^{\mu-1}e^{-y}dy, \\ \Gamma_{k+1} = \int_{\frac{\mu}{\Omega}N_r\nu_{k+1}}^{\infty} y^{\mu-1}e^{-y}dy. \end{cases} \tag{16}$$

Therefore, the average transmission rate is derived through the following formula:

$$E(c) = 0 \times P_r(C=0) + \sum_{i=1}^{K} c_i \times P_r(C=c_i) = \sum_{i=1}^{K} c_i \times P_r(C=c_i). \tag{17}$$

4 FL-CFT: a high-integrity fuzzy logic-based cooperative file transfer scheme

4.1 Overview of FL-CFT

An overview of FL-CFT is presented as follows. When a vehicle, e.g., R, needs a file, it broadcasts a resource request message to its neighboring vehicles. If a neighbor vehicle has the file, e.g., S, it sends a response message back and prepares for the file transfer. Before the file transfer, evaluation of the transmission capability from S to R is accomplished to decide whether cooperative vehicles are needed or not. If two vehicles can complete the file transfer within their connection time, R downloads the file directly without establishing a cluster. Otherwise, a cluster of vehicles in a linear topology along the road are formed for relay; the fuzzy logic is adopted to select the most eligible cooperative vehicle as the cluster members according to their relative velocity, distance, and predicted connection time. Figures 3 and 4 illustrate the case in which three cluster members are used to collect the file pieces and forward to R.

Figure 5 shows the operations of protocol. The key of the proposal is to select the optimal relay path from S to R. The fuzzy logic approach is applied due to the efficiency of the algorithm; to select appropriate cluster members using the fuzzy logic scheme, the connection time between two vehicles is evaluated and used as the input to the scheme. In what follows, we present the details of the protocol.

4.2 Transmission capability between two vehicles

In order to evaluate the transmission capability between two vehicles, the pieces-based file transfer model is first developed in our work, which is illustrated in Fig. 6.

It is assumed that the file content is equally divided into m pieces denoted by $\mathbb{M} = \{g_1, g_2, ..., g_m\}$ with the size of each piece s. During the whole connection time $\Delta T_{i,S}$, vehicle i ($i \in \mathbb{N}$) can not exactly download integral pieces since it is out of the communication range of S, resulting in the failed connection L_i between i and S while the nth piece is transferring. Therefore, according to the predicted connection time $\Delta T_{i,S}$, the number of pieces n_i is derived by

$$n_i = \left\lfloor \frac{E(c) \times \Delta T_{i,S}}{s} \right\rfloor, \tag{18}$$

where $\lfloor \cdot \rfloor$ denotes the floor function, $E(c)$ denotes the average transmission rate which can be obtained by formula (17). Besides, in Fig. 6, Δt^0 denotes the time spent on downloading n_i pieces completely, $\Delta t'$ denotes the time $\Delta T_{i,S}$ minus Δt^0 and during which the nth piece can not be downloaded completely. Their relationship is formulated as

$$\Delta t' + \Delta t^0 = \Delta T_{i,S}, \tag{19}$$

$$\Delta t^0 = \frac{n_i \times s}{E(c)}. \tag{20}$$

In our proposed scheme, once finishing transferring the n_i^{th} piece, S selects another cooperative vehicle j ($j \in \mathbb{N}$) to transfer file pieces and establishes the link L_j. Through this method, such data loss $D_{\text{loss}} = \Delta t' \times E(c)$ will be transmitted to vehicle j and it is of great importance for fully utilizing the wireless resource and saving transfer time. Consequently, the communication capability $C_{i,S}^c$ between any vehicle i and S is formulated as

$$C_{i,S}^c = s \cdot \left\lfloor \frac{E(c) \times \Delta T_{i,S}}{s} \right\rfloor. \tag{21}$$

In the cooperative phase, if several vehicles are in the communication range of S, it will transfer the file pieces to the vehicle with the highest eligible value calculated by fuzzy logic system.

4.3 Fuzzy logic-based cooperative vehicle selection

In this subsection, we introduce the fuzzy logic system in detail. Since data rate C is given by

$$C = W\log_2\left(1 + \frac{P}{N_0 W d^{\alpha}}\right), \tag{22}$$

where W denotes the channel bandwidth, P denotes the transmit power of the vehicle, d denotes the distance between S and cooperative vehicle, α denotes the path loss exponent, and N_0 denotes the white Gaussian noise [30]. Therefore, C will increase with the decrease of d. Besides,

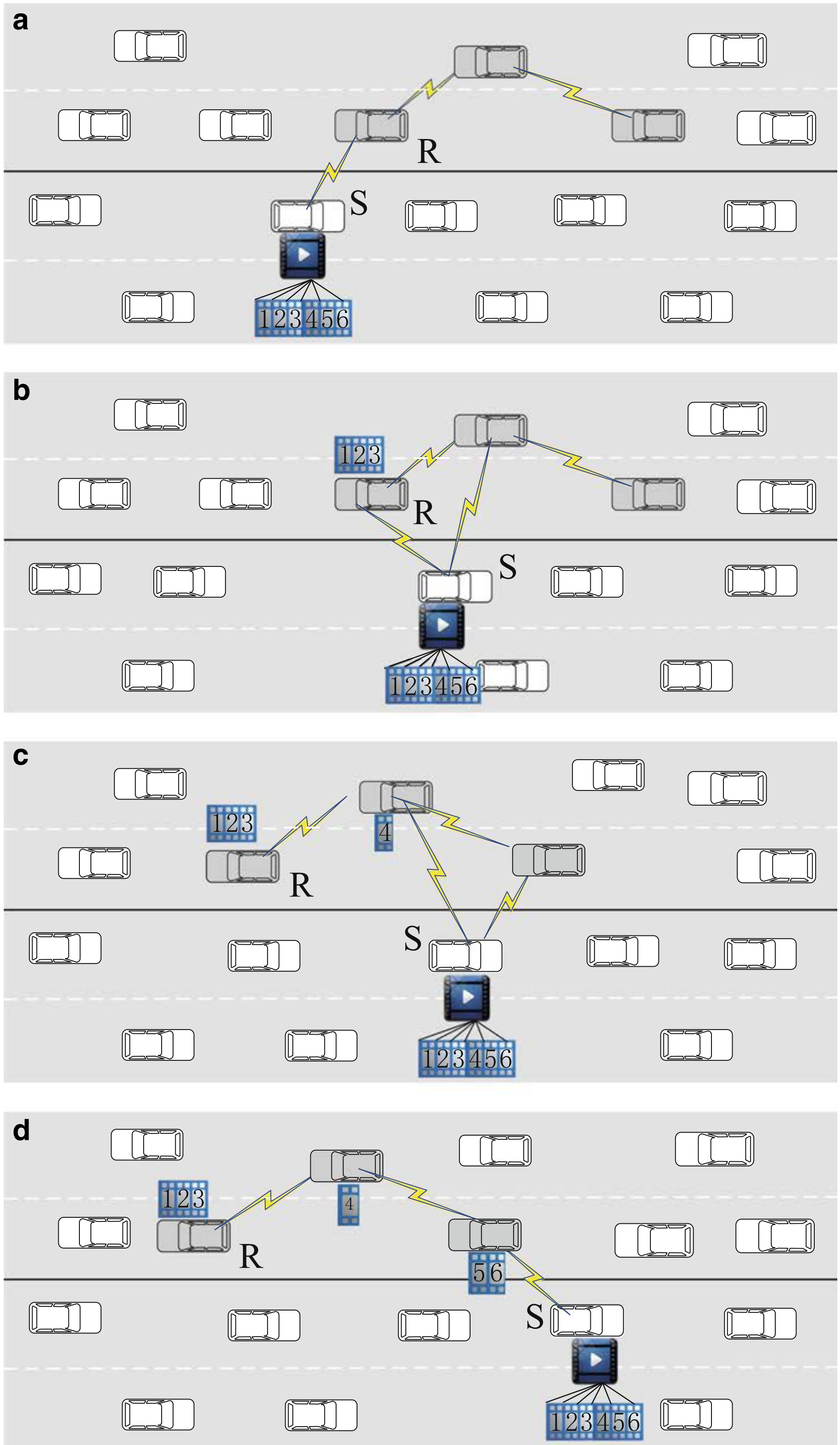

Fig. 3 Cooperative file transfer. **a** Transfer to the first cooperative vehicle, **b** Transfer to the second cooperative vehicle, **c** Transfer to the third cooperative vehicle and **d** Transfer to cooperative vehicles complete

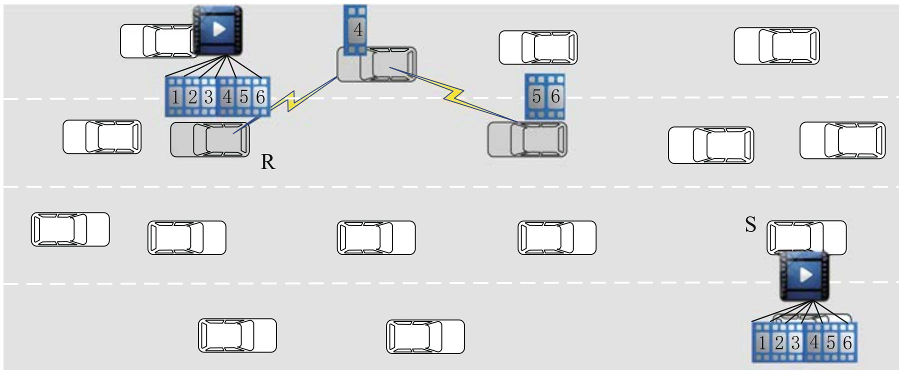

Fig. 4 Cluster members forward file pieces to request vehicle

the relative velocity also has a great influence on C since high mobility leads to unstable connection. More importantly, we also consider the connection time as an impact factor. However, finding an optimal relay subject to the three constrains is an NP-complete problem that cannot be exactly solved in polynomial time. The relay selection problem can benefit from fuzzy logic method due to the efficiency of the method to solve the NP-complete problem. The three parameters of vehicles, i.e., the relative velocity, distance, and predicted connection time, are fed through a fuzzy inference system to compute the value of eligible level, which can be used as a metric to select the most eligible relay.

4.3.1 Fuzzy logic

A fuzzy logic system describes the relationship between crisp inputs and output variables with the help of fuzzy control rules provided by the fuzzy system designer. A fuzzy logic system, as shown in Fig. 7, mainly includes *fuzzification, fuzzy control rule base, fuzzy inference*, and *defuzzication*. Fuzzification is responsible for the conversion of numerical input variable into linguistic input using input fuzzy membership functions, while defuzzification converts the fuzzy output to decisive value based on output membership functions and corresponding membership degrees. And the fuzzy inference maps the fuzzy value to pre-defined IF-THEN-based rules and calculates the fuzzy output.

Goal: determine the cooperative vehicle and cluster size, finish high-integrity file transfer.

① establish mobility model and connection time prediction model to predict connection time.

② evaluate V2V throughput through V2V communication model.

③ establish pieces-based file transfer model to avoid failed connection link.

④ apply fuzzy logic approach to select the most eligible vehicle as relay cluster member.

Improve the throughput

Output: connection time, throughput, communication capability, maximum file transfer volume and cluster size.

Fig. 5 Block diagram of various models

4.3.2 Calculation of multiple factors

As described above, three vehicle parameters having impact on the system performance are considered as fuzzy logic inputs. In order to utilize fuzzy membership function, we first calculate the three impact factors:

Related velocity factor: upon reception of the velocity information included in the request from a neighboring cooperative vehicle, S calculates a related velocity factor (RVF) as

$$v_i^{\mathsf{RVF}} = \frac{\left|\vec{V}_i - \vec{V}_S\right|}{2V_{\max}}, \tag{23}$$

where $\vec{V}_i$ and $\vec{V}_S$ denote the velocities of neighboring cooperative vehicle and S, respectively, $V_{\max}$ denote the vehicle's maximum speed.

Distance factor: upon reception of the location information included in the request from a neighbor cooperative vehicle, S calculates a distance factor (DF) as

$$d_i^{\mathsf{DF}} = \frac{\sqrt{(x_i - x_S)^2 + (y_i - y_S)^2}}{r}, \tag{24}$$

where (x_i, y_i) and (x_S, y_S) denote the location of neighboring cooperative vehicle and S, respectively.

Predicted connection time factor: upon reception of the velocity and location information included in the request from a neighboring cooperative vehicle, S calculates the predicted connection time ΔT_{iR} according to formula (5), and further calculates a predicted connection time factor (PCTF) as

$$t_i^{\mathsf{PCTF}} = \frac{\Delta T_{iS}}{\tilde{T}}, \tag{25}$$

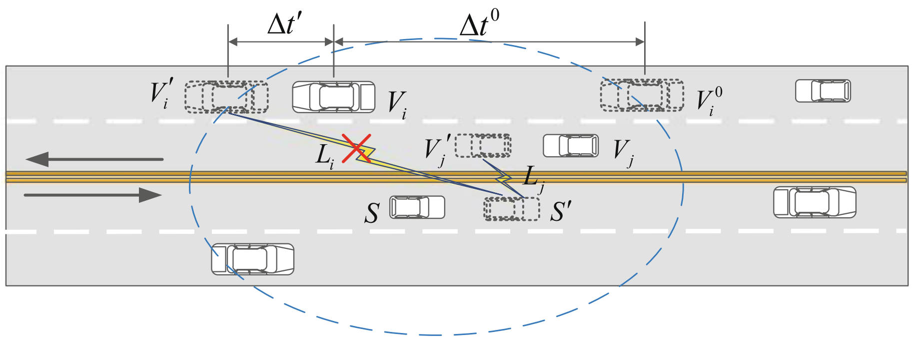

Fig. 6 Pieces-based file transfer model. *S* selects another vehicle (V_j) to transfer pieces once the predicted amount of pieces have been transferred to the current vehicle (V_i)

where $\tilde{T}$ is formulated by

$$\tilde{T} = \frac{2r}{|\vec{V}_i - \vec{V}_S|}. \tag{26}$$

4.3.3 Fuzzification

The process of converting a numerical value to a fuzzy value using a fuzzy membership function is called fuzzification. We use triangular membership function to convert the three numerical inputs to linguistic variables, which is formulated as formula (27). The membership functions of RVF, DF, and PCTF are described in formula (28), formula (29), and formula (30), respectively. Correspondingly, their fuzzy membership functions are as shown in Figs. 8, 9, and 10. *S* uses the membership functions to calculate which degree the RVF, DF, and PCTF belongs to {*fast, medium, slow*}, {*small, medium, large*}, and {*short, medium, long*}, respectively.

$$\mu_1(x) = \begin{cases} \frac{x-a}{b-a}, a \le x \le b \\ \frac{c-x}{c-b}, b \le x \le c \\ 0, \text{otherwise.} \end{cases} \tag{27}$$

$$\mu_1(\text{RVF}) = \{(a,b,c)|a,b,c \text{ are the coefficients for } \mathcal{F}_{\text{RVF}}{}^{\mathcal{S}}, \mathcal{F}_{\text{RVF}}{}^{\mathcal{M}}, \mathcal{F}_{\text{RVF}}{}^{\mathcal{F}}\} = \{(\text{-}0.5,0,0.5), (0,0.5,1), (0.5,1,1.5)\} \tag{28}$$

$$\mu_1(\text{DF}) = \{(a,b,c)|a,b,c \text{ are the coefficients for } \mathcal{F}_{\text{DF}}{}^{\mathcal{S}}, \mathcal{F}_{\text{DF}}{}^{\mathcal{M}}, \mathcal{F}_{\text{DF}}{}^{\mathcal{L}}\} = \{(\text{-}0.5,0,0.5), (0,0.5,1), (0.5,1,1.5)\} \tag{29}$$

$$\mu_1(\text{PCTF}) = \{(a,b,c)|a,b,c \text{ are the coefficients for } \mathcal{F}_{\text{PCTF}}{}^{\mathcal{S}}, \mathcal{F}_{\text{PCTF}}{}^{\mathcal{M}}, \mathcal{F}_{\text{PCTF}}{}^{\mathcal{L}}\} = \{(\text{-}0.5,0,0.5), (0,0.5,1), (0.5,1,1.5)\} \tag{30}$$

4.3.4 Fuzzy inference

The fuzzy inference engine is based on fuzzy IF-THEN-based rules, which are ultimately written by a professional designer in the related field. The design of the knowledge-based rules is based on our understanding of the characteristics of VANETs [37]. Once the fuzzy values of related velocity factor, distance factor, and predicted connection time factor have been calculated and converted to linguistic variables, *S* uses the IF-THEN rules, as defined

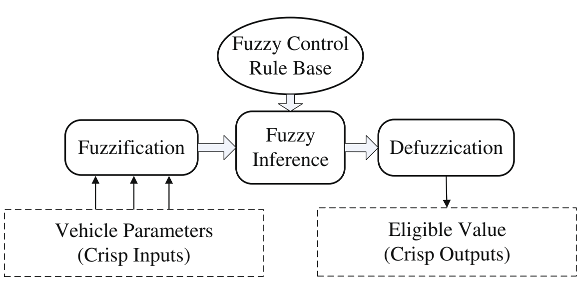

Fig. 7 Fuzzy logic system

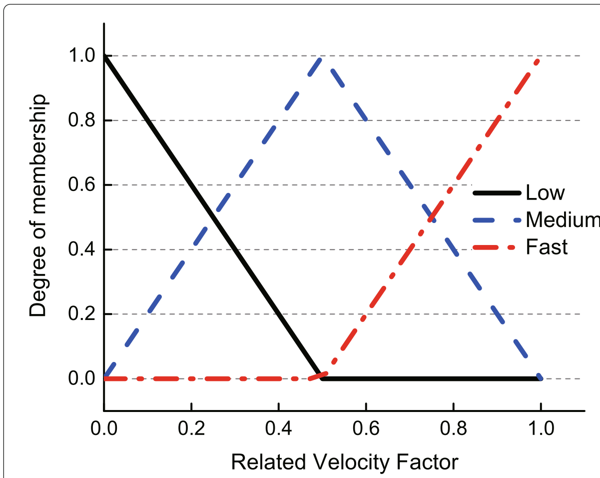

Fig. 8 Membership function of the related velocity input

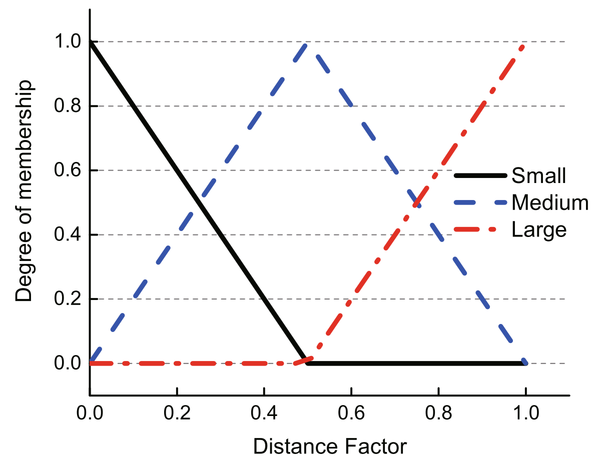

Fig. 9 Membership function of the distance input

in Table 2, to calculate the eligible value of each cooperative vehicle. The linguistic variables of the eligible value are belong to the fuzzy sets as {*very high, high, medium, low, very low*}. For example, in Table 2, Rule 2 may be expressed as **IF** related velocity is slow, distance is small, and predicted connection time is medium, **THEN** eligible value is high.

Through the fuzzy logic tool in Matlab, the relationships between output and any two inputs are depicted in the form of 3D, as shown in Figs. 11, 12, and 13.

4.3.5 Defuzzication

A mathematical method that extracts a crisp output value from the aggregation of the fuzzy output representation is called defuzzification. Centroid defuzzification method is applied in this work, which is the most commonly used technique and is very accurate. The centroid defuzzification technique can be expressed as

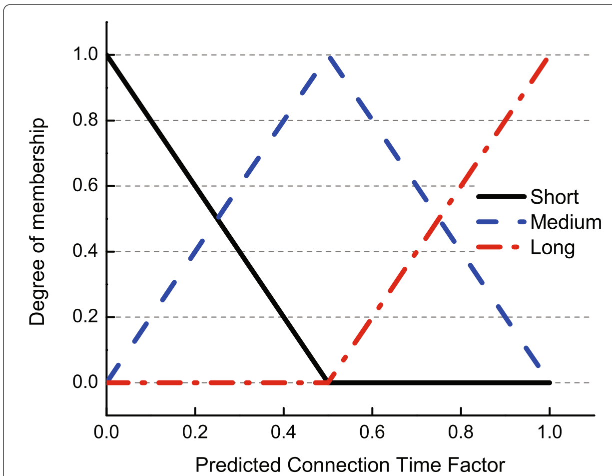

Fig. 10 Membership function of the predicted connection time input

Table 2 If-then rules base

Rule no.	If (And)			Then
	Related velocity Factor (RVF)	Distance factor (DF)	Predicted connection time factor (PCTF)	Eligible value
1	Slow	Small	Short	Medium
2	Slow	Small	Medium	High
3	Slow	Small	Long	Very high
4	Slow	Medium	Short	Low
5	Slow	Medium	Medium	Medium
6	Slow	Medium	Long	High
7	Slow	Large	Short	Very low
8	Slow	Large	Medium	Low
9	Slow	Large	Long	Medium
10	Medium	Small	Short	Low
11	Medium	Small	Medium	Medium
12	Medium	Small	Long	High
13	Medium	Medium	Short	Low
14	Medium	Medium	Medium	Medium
15	Medium	Medium	Long	High
16	Medium	Large	Short	Very low
17	Medium	Large	Medium	Low
18	Medium	Large	Long	Medium
19	Fast	Small	Short	Very low
20	Fast	Small	Medium	Low
21	Fast	Small	Long	Medium
22	Fast	Medium	Short	Very low
23	Fast	Medium	Medium	Low
24	Fast	Medium	Long	Medium
25	Fast	Large	Short	Very low
26	Fast	Large	Medium	Very low
27	Fast	Large	Long	Low

$$\mathrm{EV} = \frac{\int \mu_2(x) \times x dx}{\int \mu_2(x) dx}, \tag{31}$$

where $\mu_2(x)$ represents the output membership function, which is also triangular, as defined in formula (32) and formula (33), and is depicted in Fig. 14, x denotes the output variable, EV denotes the dufuzzified output, i.e., the numerical eligible value.

$$\mu_2(x) = \begin{cases} \frac{x-d}{e-d}, d \le x \le e \\ \frac{f-x}{f-e}, e \le x \le f \\ 0, \text{otherwise.} \end{cases} \tag{32}$$

$$\mu_2(\mathrm{RVF}) = \{(d,e,f)|d,e,f \text{ are the coefficients for } \mathcal{F}_{\mathcal{EV}}{}^{\mathcal{VS}}, \mathcal{F}_{\mathcal{EV}}{}^{\mathcal{S}}, \mathcal{F}_{\mathcal{EV}}{}^{\mathcal{M}}, \mathcal{F}_{\mathcal{EV}}{}^{\mathcal{H}}, \mathcal{F}_{\mathcal{EV}}{}^{\mathcal{VH}}\} = \{(-0.25,0,0.25), (0,0.25,0.5), (0.25,0.5,0.75), (0.5,0.75,1), (0.75,1,1.25).\} \tag{33}$$

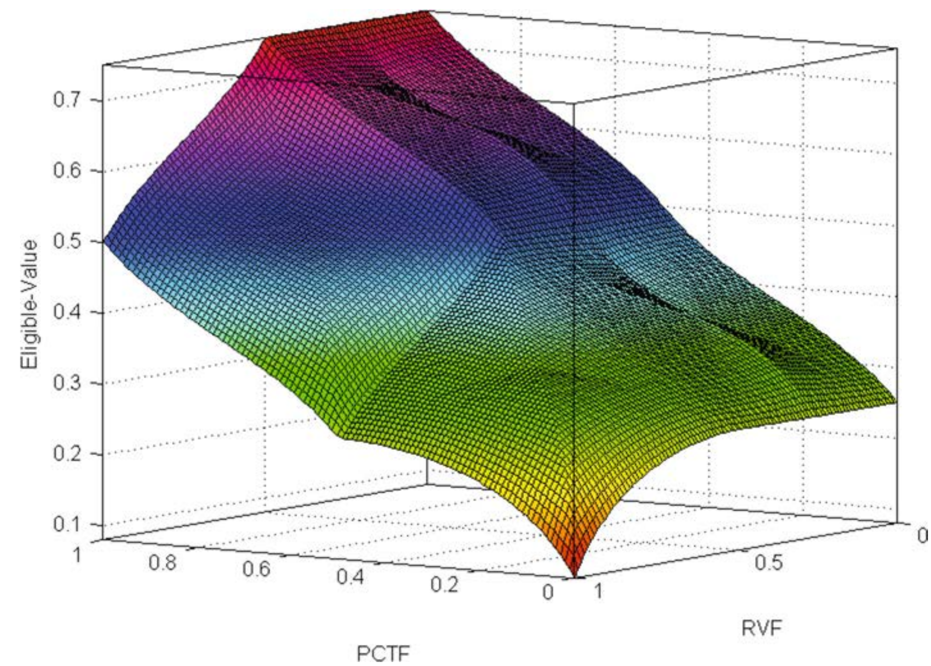

Fig. 11 Impact of RVF and PCTF on output

4.4 Cluster establishment

With FL-CFT, if a vehicle cannot download the required content file completely from *S* within the connection time between them, the vehicle will establish a linear cluster and cooperate with other cluster members to download the file.

There exist many methods to establish a cluster in VANETs. The key problem is how to find the vehicles that have similar characteristics as cluster members [29]. The proposed scheme establishes a cluster according to the following steps.

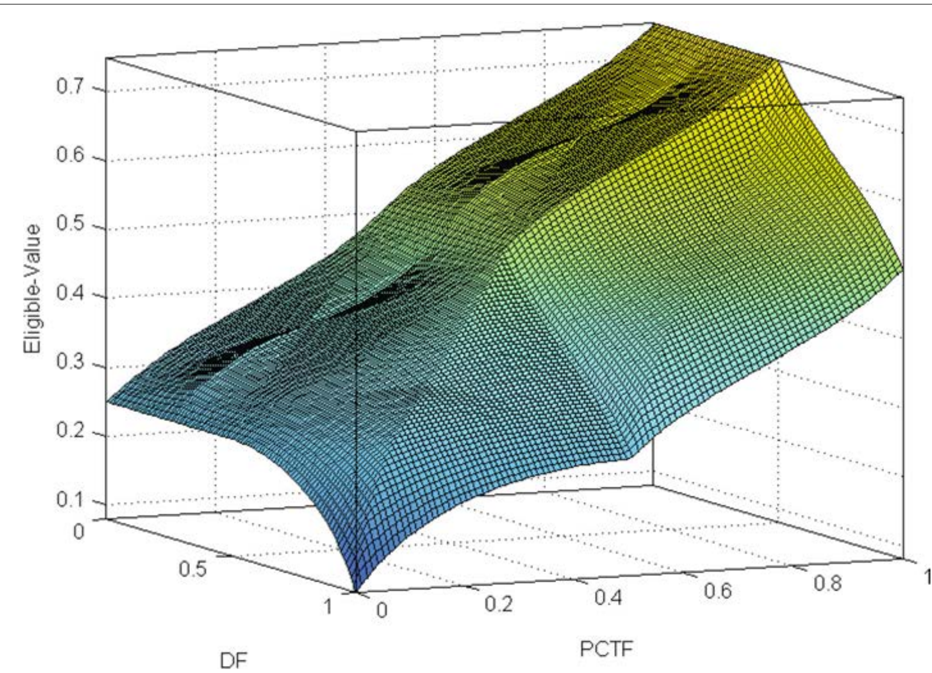

Fig. 12 Impact of DF and PCTF on output

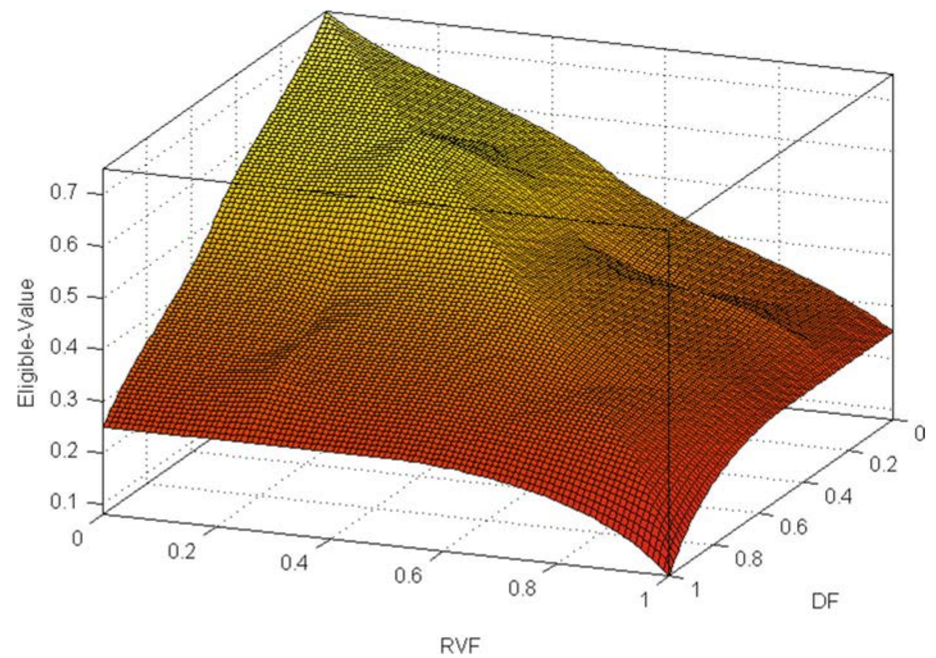

Fig. 13 Impact of DF and RVF on output

Step 1: the request vehicle first broadcasts a request packet for cooperative file transfer, then a neighboring vehicle which is within the communication range and willing to assist sends back an ACK. If the request vehicle receives the ACK, it will request the basic information, such as velocity and location from the neighboring vehicle. Thereafter, the appropriate neighboring vehicle will be invited to join the cluster and become one of cluster members.

Step 2: the neighboring vehicle that joins the cluster continues to broadcast the request packet for cooperative file transfer and invites its neighbors to join the cluster. Then the basic information about the newly added cluster member is forwarded to the request vehicle. Step 2 is repeated until enough cluster members have jointed the cluster.

Step 3: after finishing the file piece transfer to the present cooperative vehicle, S calculates the EV (eligible value) of each cooperative vehicle that is within it's communication range through fuzzy logic system, and then transfers file pieces to the vehicle with the highest *EV* value.

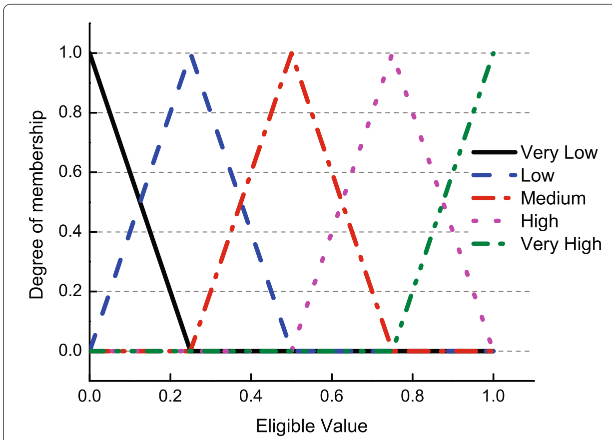

Fig. 14 Output membership function of eligible value

According to the vehicle-to-vehicle communication model mentioned previously, we are able to calculate the amount of file size each cooperative member can download. Therefore, the number of vehicles that should be contained in the cluster can be derived. Assuming that the size of the file to be transferred is V_{file}, the size of all file pieces that vehicle i in can download is V^i_{data} and the number of the required vehicles (i.e., the size of the cluster) is N_c, then V^i_{data} and N_c are derived by using the following formulas:

$$V^i_{\text{data}} = C^c_{i,S}, \tag{34}$$

$$N_c = \left\{ \min\{n\} \mid \sum_{i=1}^{n} V^i_{\text{data}} \geq V_{\text{file}}, n = 1, 2, \cdots \right\}. \tag{35}$$

4.5 Cooperative vehicle transfer file pieces to request vehicle

After cluster members collect the required file pieces, they forward their pieces to the request vehicle. In our work, the IEEE 802.11b DCF mechanism is adopted as the MAC protocol of the network and the RTS/CTS mechanism is employed to avoid the hidden terminal problem. Furthermore, we set the back-off time as a constant back-off window size. Therefore, the average transmission probability of each vehicle is formulated as

$$\zeta = \frac{2}{W+1}. \tag{36}$$

In order to calculate the success probability of packet transmission, it is assumed that n nodes compete for one channel where n obeys Poisson distribution and its probability mass function is formulated as

$$f_n(x) = \frac{(\rho R_{\mathrm{cs}})^x}{x!} \exp(-\rho R_{\mathrm{cs}}), \tag{37}$$

where ρ denotes the traffic density parameter, R_{cs} denotes the diameter of carrier sense range of a vehicle. Then the probability that a node successfully sends packets in any slot can be derived as

$$P_{\mathrm{suc}} = \frac{n\zeta(1-\zeta)^{n-1}}{1-(1-\zeta)^n}. \tag{38}$$

Accordingly, the throughput between two vehicles can be derived as

$$R_{\mathrm{thr}} = \frac{E[\,V_{\mathrm{payload}}]}{E[\,\text{length of a slot time}]} = \frac{P_{\mathrm{suc}}L_{\mathrm{p}}}{T}[\,1-(1-\zeta)^n]\,, \tag{39}$$

where V_{payload} denotes the payload information volume transmitted successfully in a slot time, L_{p} denotes the average length of a packet, and T is the average length of a slot which is formulated in [10].

Consequently, the size of file that can be transferred between cooperative vehicle i and request vehicle R within their connection time can be calculated using the connection time $\Delta T_{i,R}$ that can be obtained using formula (5), and the throughput R_{thr} that can be obtained using formula (17).

5 Simulation

In our work, we study the performance of FL-CFT via extensive theoretical analysis and Matlab-based simulations. Our detailed experimental results are presented in this section. Specifically, the performance of FL-CFT is investigated in terms of average connection time, average throughput, average transmission capability, maximum file transfer volume, and cluster size. We also compare FL-CFT with two of the state-of-the-art schemes, IOCT [10] and CFT [12], to understand the advantages and disadvantages of FL-CFT. What follows, the detailed experimental results are presented in this section.

5.1 Simulation settings

In our simulations, a freeway model [38] is adopted where vehicles travel on a bi-directional highway with two lanes per direction. The major parameters are summarized in Table 3. We use the IEEE 802.11b DCF mechanism as the MAC protocol and V2V communication protocol as the wireless communication protocol. In addition, the RTS/CTS mechanism is adopted to avoid the hidden terminal problem.

5.2 Simulation results

5.2.1 Average connection time

Figure 15 shows the impact of different traffic densities and communication ranges on the average connection time when SD = 150 m. Note that ρ denotes the number of vehicles per kilometer. We can observe that, with the communication range increases, the average connection time increases. When the communication range is 250 m, the average connection time is 5.3 s. When the communication range is 600 m, the average connection time is about 12.7 s. And the average connection time does not vary significantly with the densities.

5.2.2 Average throughput

The impact of traffic density and communication range on the average throughput between two vehicles is shown in Fig. 16. We can observe that when $\rho = 5$ and the communication range varies from 250 to 600 m, the average throughput of CFT varies from 6.6 to 8.0 Mbps while the average throughput of FL-CFT varies from 6.75 to 8.1 Mbps; when $\rho = 6$, the average throughput of CFT

Table 3 Simulation parameters

Parameter	Value
Length of per lane (km)	11
Width of per lane (m)	5
Minimum speed (km/h)	60
Maximum speed (km/h)	120
Traffic density ρ (car/km)	$\{5, 6, \ldots, 10\}$
Communication range of vehicle r (m)	$\{250, 300, \ldots, 600\}$
Safety distance SD (m)	{75,100,150}
Size of file piece s (MB)	8
Size of back-off window W	32
Length of a packet L_p (KB)	4.2
Length of a slot $T_{\mathrm{slot-time}}$ (us)	13
Transmission time of RTS frame (us)	53
Transmission time of CTS frame (us)	37
Transmission time of DIFS frame (us)	32
Transmission time of SIFS frame (us)	53
Transmit power P_t (W)	0.2
Hot noise power N_r (dBm)	− 96
Path loss index α	4
G_t, G_r, h_t, h_r, L	1

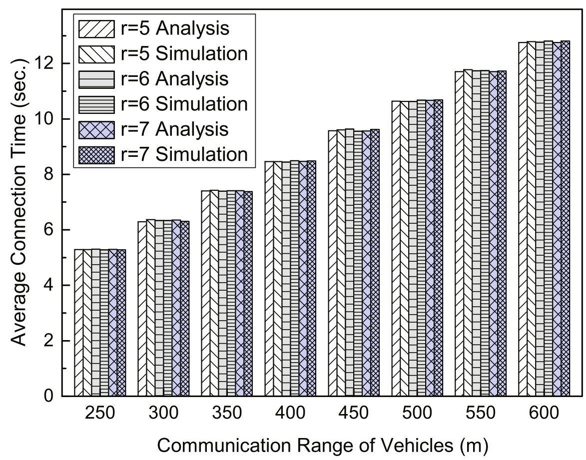

Fig. 15 Average connection time

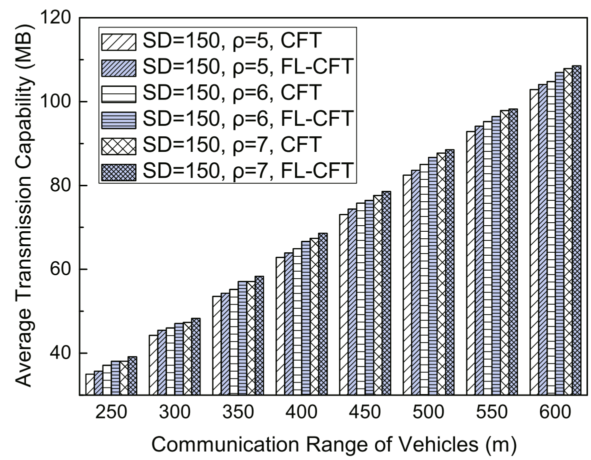

Fig. 17 Average transmission capability

varies form 6.9 to 8.2 Mbps while the average throughput of FL-CFT varies from 7.24 to 8.3 Mbps; when $\rho = 7$, the average throughput varies form 7.2 to 8.4 Mbps while the average throughput of FL-CFT varies from 7.4 to 8.5 Mbps. In summary, with the increase of either the traffic density or the communication range, the average throughput increases, and the proposed FL-CFT outperforms the CFT in terms of average throughput under the same conditions.

5.2.3 Average transmission capability

The impact of communication range and traffic density on the average transmission capability between two vehicles when SD = 150 m is shown in Fig. 17. We can observe from the figure that when $\rho = 5$ and the communication range varies from 250 to 600 m, the average transmission capability of CFT varies from 35.0 to 102.9 MB while the average transmission capability of FL-CFT varies from 35.7 to 104 MB; when $\rho = 6$, the average transmission capability varies from 37.1 to 104.8 MB while the average transmission capability of FL-CFT varies from 38.1 to 106.9 MB; when $\rho = 7$, the average transmission capability varies from 38.1 to 107.9 MB while the average transmission capability of FL-CFT varies from 39.2to 108.5 MB. The result shown in Fig. 17 reveals that the average transmission capability of both CFT and FL-CFT increases with the increase of traffic density. And with the increase of communication range, the average transmission capability of both CFT and FL-CFT linearly increases. Under the same condition, the proposed FL-CFT has a higher average transmission capability than CFT.

5.2.4 Maximum file transfer volume

Figure 18 shows the maximum file transfer volume of IOCT, CFT, and FL-CFT under different traffic densities when $r = 250\ m$. Our experimental result indicate that when ρ varies from 5 to 10, the maximum file transfer volume of IOCT varies from 35 to 45 MB, the maximum file transfer volume of CFT varies from 297 to 415 MB,

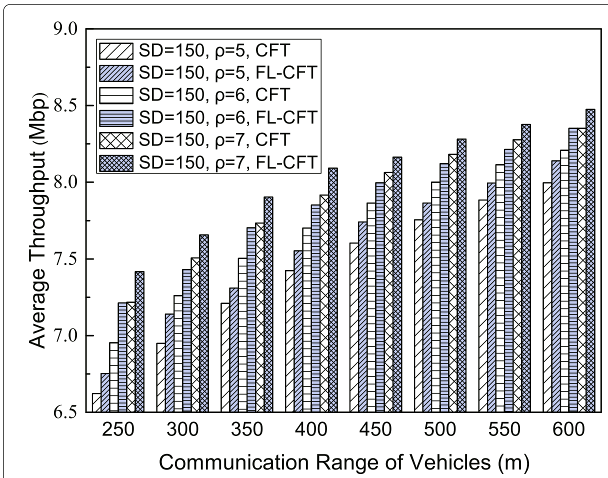

Fig. 16 Average throughput

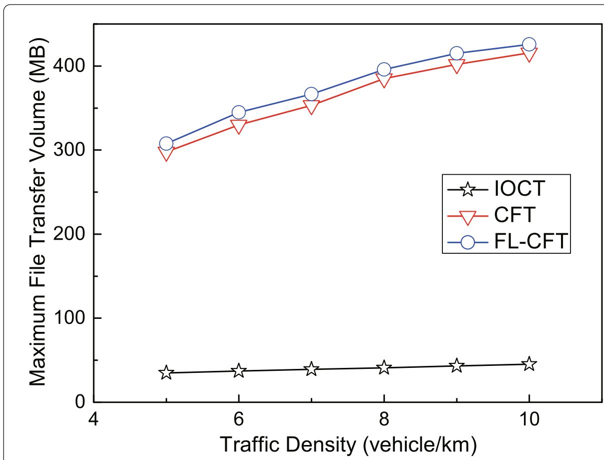

Fig. 18 Maximum file transfer volume

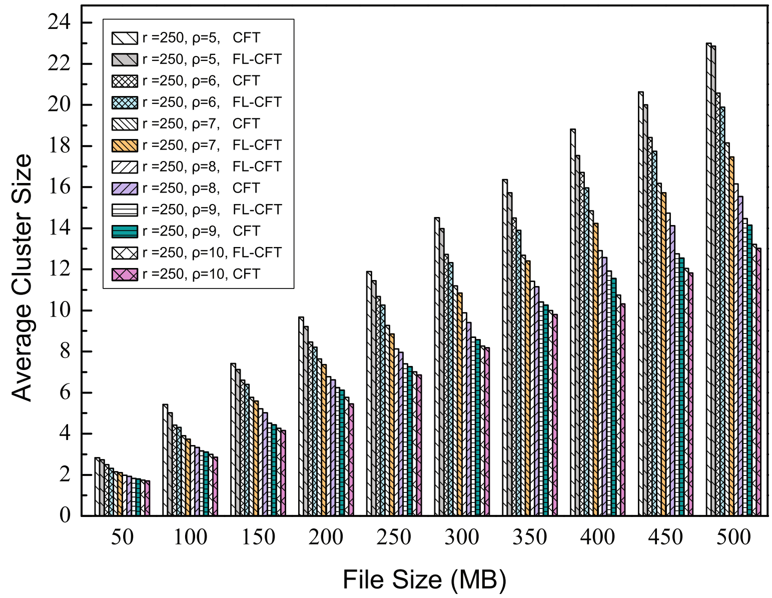

Fig. 19 Average cluster size

the maximum file transfer volume of FL-CFT varies from 307 to 425 MB. The reason why the maximum file transfer volume of CFT and FL-CFT is much greater is that a file can be transferred through multiple cluster members. More importantly, we can observe from Fig. 18 that the maximum file transfer volume of IOCT is not sensitive to traffic density, which is because IOCT only involves two vehicles. The proposed FL-CFT has a higher maximum file transfer volume than CFT as a result of adopting the fuzzy logic to select the most eligible vehicle as cooperative vehicle for improving the throughput thus improving the maximum file transfer volume. The consideration of the utilizing of fuzzy logic method contributes to the high maximum file transfer volume.

5.2.5 Cluster size

Figure 19 shows the impact of file size on the average cluster size when $r = 250\ m$. Our experimental results reveals that the average cluster size increases with the increase of file size. When $\rho = 5$, the average cluster size of CFT varies from 2.8 to 22.9 while the average cluster size of FL-CFT varies from 2.4 to 20.5. When $\rho = 10$, the average cluster size of CFT varies from 1.8 to 13.2 while the average cluster size of FL-CFT varies from 1.7 to 13.0. Given the same file size, lower traffic density leads to a greater required cluster size. Due to the higher transmission capability, the proposed FL-CFT involves less vehicles in cooperative file transfer than CFT.

6 Conclusions

Small- and medium-size file transfers are fundamental to the infotainment applications in highway vehicular networks. This however is challenged by the dynamic connections among vehicles. This paper tackles the issue by developing a fuzzy logic-based collaborative forward scheme for integrated file transfer in VANET. In specific, a cluster of vehicles, based on the evaluation of transmission capability, are selected using a fuzzy logic-based scheme. Using both analysis and simulations, we have shown that our proposal outperforms the state-of-the-art file transfer scheme in terms of the maximum file transfer volume. The detailed experimental results of FL-CFT in terms of average connection time, average throughput, average transmission capability, maximum file transfer volume, and cluster size have been presented.

In the future, we shall concentrate on developing a theoretical model for analyzing the impact of the size of file piece on the performances of the proposed scheme.

Endnotes

[1] The vehicle which issues the download request of the file is called the request vehicle in this paper.

[2] The vehicle which owns the file requested from request vehicle is called the source vehicle in this paper.

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Authors' contributions

QL proposed the original idea and wrote the paper under the guidance of XC and THL. QL designed the experiment and provided all of the figures. THL and QY checked the manuscript and contributed to the rearrangement of the materials. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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