A Distributed LT Codes-based Data Transmission Technique for Multicast Services in Vehicular Ad-hoc Networks

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Abstract

In this paper, we consider an infrastructure-vehicle-vehicle (I2V2V) based Vehicle Ad-hoc Networks (VANETs), where one base station multicasts data to d vehicular users with the assistance of r vehicular users. A Distributed Luby Transform (DLT) codes based transmission scheme is proposed over lossy VANETs to reduce transmission latency. Furthermore, focusing on the degree distribution of DLT codes, a Modified Deconvolved Soliton Distribution (MDSD) is designed to further reduce the transmission latency and improve the transmission reliability. We investigate the network behavior of the transmission scheme with MDSD, called MDLT based scheme. Closed-form expressions of the transmission latency of the proposed schemes are derived. Performance simulation results show that DLT based scheme can reduce transmission latency significantly compared with traditional Automatic Repeat Request (ARQ) and Luby Transform (LT) codes based schemes. In contrast to DLT based scheme, the MDLT based scheme can further reduce transmission latency and improve FER performance substantially, when both the source-to-relay and relay-to-sink channels are erasure channels.

Keywords: vehicle ad-hoc networks; distributed LT coding; erasure channel; transmission latency; multicast services

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1. Introduction

Automotive communication systems have drawn much attention throughout the last years as they are considered as very promising approaches to various challenges in modern vehicular environment [1]-[5]. Vehicular Ad-Hoc Networks (VANETs) provide data communications among nearby infrastructures or vehicles via vehicles-to-vehicles (V2V) protocol, vehicles-to-infrastructure (V2I) protocol and infrastructure-to-vehicles (I2V) protocol. VANET is a collection of set of On Board Unit (OBU) and set of Road Side Unit (RSU), which are the wireless devices equipped with vehicles and base stations [6]. Many authors investigate data dissemination techniques for VANETs based on vehicular communication protocols, i.e. V2V, V2I and I2V protocols, and analyze how messages are propagating in VANETs. By exchanging information in vehicular networks including V2V, V2I and I2V communications, various purposes such as local hazard warning, efficient route planning, traffic flows coordination and road traffic safety can be driven. However, vehicular networks generally lack connectivity due to high mobility and rapidly changing network [3]. Ongoing efforts are aimed at enabling inter-vehicle communications supported by network infrastructure in order to provide a real-time and reliable service.

A common technique to solve the reliable problem is to use Automatic Repeat Request (ARQ) protocols wherein a packet is retransmitted through a suitable return channel if discrepancies exist in received data bits [7]. However, ARQ protocols make it possible to increase network overhead and extra bandwidth. Alternatively, the second general technique for dealing with transmission errors by removing the reverse channel is called Forward Error Correction (FEC) with a fixed code rate, which results in unnecessary redundancy for receivers within better channel conditions [8]. Among all the FEC approaches, fountain codes are the newest and most promising one, which can overcome the disadvantages in the traditional schemes mentioned before[9][10]. Fountain codes can yield limitless encoding symbols and have flexible rate control without requiring feedback channel. LT code was developed by Luby [11] as the first practical realization of fountain codes, which is a kind of new type of forward error correction coding. The application of fountain codes to vehicular communication systems has been already proposed in [12][13]. The approach requires relay vehicles to collect a number of out-of-turn packets. Once the relay vehicles have collected the minimum amount of packets, they forward messages to destination vehicles which can finally reconstruct the original information flow. However, it is a waste of time to collect and buffer packets at relays and this process reduces the speed of data delivery in an end-to-end connection. In order to reduce latency and meanwhile retaining communication reliability, the concept of decomposed fountain codes has been proposed, which consist of two layers of data encoding performed separately by the source and relay node [14]. In particular, analysis in [15] shows that the asymptotic performance of decomposed LT codes is the same as that of the corresponding non-decomposed LT code. Distributed LT (DLT) codes belong to Decomposed LT codes, proposed in [16] [17]. DLT codes generate each packet with two layers of random encoding. The detailed process of DLT encoding will be introduced in Section 3.2.

In this paper, we consider the application scenario where network infrastructure, i.e. base station, multicasts the entertainment services or informs an emergency such as a traffic jam or a traffic accident to d vehicular users with the assistance of r vehicular users. A novel application of distributed LT codes (DLT) is proposed to reduce transmission latency in VANETs. Then, we propose an improved transmission scheme called MDLT based scheme, which adopts the modified degree distribution, called Modified Deconvolved Soliton Distribution (MDSD), to encode codeword at the source. This scheme can further reduce transmission latency and meanwhile improve communication reliability. Transmission latency of ARQ based scheme, LT based scheme, DLT based scheme and MDLT based scheme are also analyzed, respectively. We provide Monte Carlo simulations on transmission latency and FER when there are erasures in both source-relay and relay-sink channels. From the simulations, MDLT based scheme shows significantly better performance than DLT based scheme in transmission latency and FER. Moreover, the DLT and MDLT based schemes reduce the transmission latency compared with the traditional schemes, ARQ based scheme and LT based scheme, at the acceptable cost of FER.

The rest of the paper is organized as follows. We describe the system model in Section 2. In Section 3, we propose the transmission scheme based on DLT codes in VANETs. The improved transmission scheme based on Modified Deconvolved Soliton Distribution (MDSD) is designed in Section 4. The analysis of transmission latency is introduced in Section 5 for four schemes: ARQ scheme, LT scheme, DLT scheme and MDLT scheme. Monte Carlo simulation results and discussions are provided in Section 6. Finally, Section 7 concludes the paper.

2. System Model

Consider an I2V2V network where a source S communicates with d destinations $D=\{D_1,D_2,...,D_d\}$ with the assistance of r decode-and-forward (DF) relays $R=\{R_1,R2,\dots,R_r\}$ as shown in **Fig. 1**. Due to the shadowing and the limited transmission power, the direct paths between the source and the destinations are not available. We use DF realys to get high reliability [18] and TDD-capable relays which send and receive data at different time slots. Node S is associated with the data sets of k packets. As shown in **Fig. 1**, the transmission is divided into two consecutive phases. 1) I2V: The base station multicasts packets to relay vehicles moving within the range of the base station. 2) V2V: Destination vehicles collect packets from different relay vehicles to recover the whole data flow.

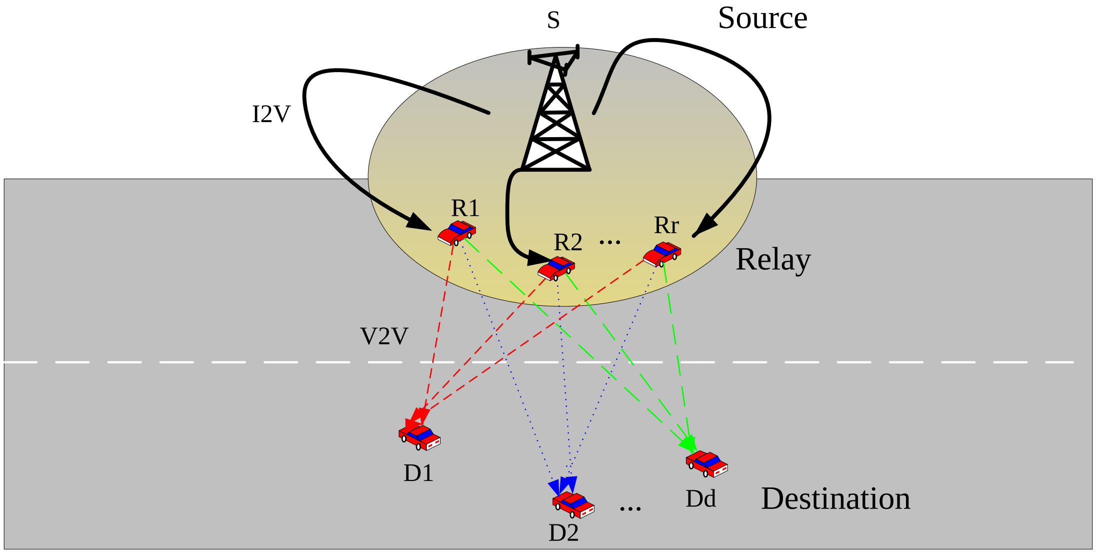

Fig. 1. The application scenario of the proposed technique. The base station multicasts messages to relay vehicles via I2V; messages are then delivered from relay vehicles to destination vehicles via V2V.

The error free and lossy states of each channel can be modeled as alternating time intervals of good and bad states with random durations. In the VANETs, current state has much relation with previous state. For example, if the vehicles pass through a tunnel, the channels' states keep bad for a sequence of time slots. We assume that the erasure channels follow a discrete-time Markov chain (DTMC) with two states at a certain channel [19], namely, good (S(t)=1) and bad (S(t)=0), as shown in **Fig. 2**. We note that packets can be received successfully when the state is good and packets will be lost when the state is bad. The channels are denoted as L_{ij} ($i \in \{S, R\}$, $j \in \{R, D\}$) and the probability of good state at L_{ij} is represented by P_{ij}. The link L_{ij} changes from good state to bad state with probability p_{ij} and changes from bad state to good state with probability q_{ij}. The stationary probabilities of good state and bad state are represented by P_G and P_B and given by (1) and (2) respectively. Without loss of generality, we consider the simplified model shown in **Fig. 3**. For example, the probability of good state at SR_1 (L_{01}) is represented by P_{01}. Similarly, P_{02}, P_{11}, P_{12}, P_{21}, P_{22} indicate the probability of good state at SR_2 (L_{02}), R_1D_1 (L_{11}), R_1D_2(L_{12}), R_2D_1 (L_{21}), R_2D_2 (L_{22}) respectively.

$$P_G = \Pr\{S(t)=1\} = P_{ij} = \frac{q_{ij}}{p_{ij}+q_{ij}}, \quad (1)$$

$$P_B = \Pr\{S(t)=0\} = 1-P_{ij} = \frac{p_{ij}}{p_{ij}+q_{ij}}, \quad (2)$$

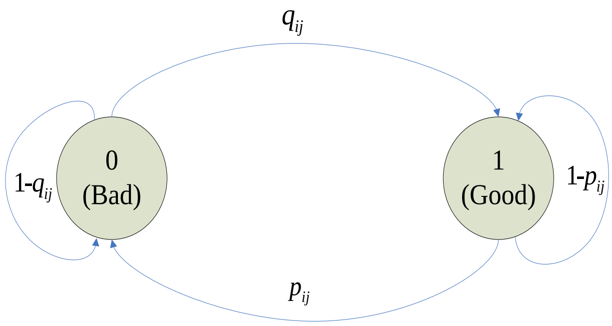

Fig. 2. Two-state DTMC model for states of channel L_{ij}.

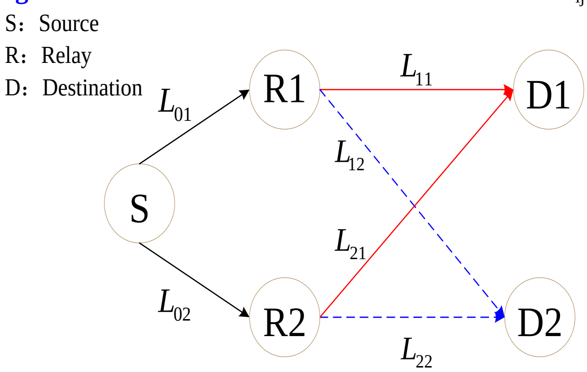

Fig. 3. The simplified model of application scenario.

3. DLT based Scheme

In this section, we first briefly introduce the traditional transmission schemes---ARQ based scheme and LT based scheme over the I2V2V communication shown in **Fig. 3**. Then a DLT codes based vehicular transmission scheme (DLT based scheme) in the network of **Fig. 1** is designed.

3.1 Traditional Transmission Schemes: ARQ Based Scheme and LT Based Scheme

In this subsection, we briefly introduce the methods of ARQ based scheme and LT based scheme in the network of **Fig. 3**.

ARQ based scheme: The source first multicasts an uncoded packet to the relay vehicles, then the relays send feedbacks to the source. If no relay receives this packet, the source multicasts the current packet again. Otherwise, the relays receiving the packet successfully multicast current packet to all the destinations. Next, the destinations will send a feedback to the relays. If the relays are informed that the packet has been received by all the destinations, the next packet will be delivered from the source. Otherwise, the lost packet is multicasted by the relays receiving the packets from the source successfully again.

In addition to the operational details of the scheme mentioned above, we assume that all the nodes operate in half duplex mode and all the feedback channels are assigned orthogonal channels. The detailed description of the protocol showing the transmitting nodes, their channel assignments (time slots) and the respective transmitted messages are shown in **Table 1**.

Table 1. Protocol description of ARQ based scheme

Time slot	Transmitter	Message	Receiver	Note
1	S	Current packet	R_1 and R_2	S to R
2	R_1 and R_2	Feedback	S	R to S
3(1)	Repeat 1-2			Both R_1 and R_2 unsuccessful
3(2)	Successful R_1 or R_2	Current packet	D_1 and D_2	R_1 or R_2 successful
4	D_1 and D_2	Feedback	R_1 and R_2	D to R
5(1)	Repeat 3(2)-4			D_1 or D_2 unsuccessful
5(2)	S	Next packet	R_1 and R_2	Both D_1 and D_2 successful

LT based scheme: The source multicasts LT codes based packets sequentially to the relays, then the relays collect and buffer the data messages as long as they enter the infrastructure's radio range. Symbol k denotes the number of source packets and ε ($0<\varepsilon<1$) is the redundant proportion needed by the destinations to recover all the source packets. Once the number of diverse packets received respectively by R_1 and R_2 satisfies $n=k(1+\varepsilon)>k$, relay vehicles start to decode and keep encoding LT codes based packets to the destinations until all the destinations send back an Acknowledgement (ACK). Because of the high speed mobility of vehicles, R_1 and R_2 may not receive enough packets to decode when they are in the radio range of the base station. They need to communicate the information of received packets with each other when they are without the range of the source. For example, R_1 first enters into the range of the source, and then it collects and buffers the packets from time slot 1 to time slot $i_1=\delta_1 \cdot k \cdot (1+\varepsilon)$. Next, R_2 repeats the process from time slot i_1+1 to time slot $i_2=\delta_2 \cdot k \cdot (1+\varepsilon)$.

For briefly, we assume δ_1=0.5, δ_2=1 and one packet is delivered in one time slot. So, R_1 can receive Packet[1] to Packet[$k(1+\varepsilon)/2$] and R_2 can receive Packet[$k(1+\varepsilon)/2+1$] to Packet[$k(1+\varepsilon)$].

In addition to the operational details of the scheme mentioned above, we assume that all the nodes operate in half duplex mode and R_1 and R_2 receive the same number of diverse packets when they are within the range of the source. Packet[1] to Packet[$k(1+\varepsilon)$] are diverse LT codes based packets. The detailed description of the protocol showing the transmitting nodes, their channel assignments (time slots) and the respective transmitted messages are shown in **Table 2**.

Table 2. Protocol description of LT based scheme

Time slot	Transmitter	Message	Receiver	Note
1 *to* i_1	S	Packet[1]-Packet[i_1]	R_1	R_1 within the range of S
i_1+1 *to* i_2	S	Packet[i_1+1]-Packet[i_2]	R_2	R_2 within the range of S
i_2+1 *to* i_3	R_1	Packet[1]-Packet[i_1]	R_2	R_1 and R_2 without the range of S
i_3+1 *to* i_4	R_2	Packet[i_1+1]-Packet[i_2]	R_1	R_1 and R_2 without the range of S
i_4+1 *to* i_5	R_1 and R_2	Recoded packets	D_1 and D_2	R recode to D

3.2 DLT Based Scheme

In this subsection, we propose a DLT codes based transmission scheme in the network of **Fig. 1**. In the traditional technique of DLT codes proposed in [16], there are two sources and one common relay. DLT codes can be used to independently encode data from multiple sources and the two DLT encoded packets are either XORed or selected alternatively to transmit at the common relay. The resulting bits stream (called MLT codes) have a degree distribution approximating the degree distribution of LT codes, where the degree distribution determines the probability of the degree (number of data packets XORed to generate each encoded packet). So the degree distribution at each source is deconvolved of the degree distribution of LT codes. Different from the traditional technique of DLT codes in [16], there is only one source in the scenario denoted in the system. We first divide k source packets into two sets k_1 and k_2 which both contain $k/2$ packets in advance. DLT codes generate each code with two layers of encoding. 1)Source-relay: DLT codes based packets are sequentially generated from two sets at the source based on Deconvolved Soliton Distribution (DSD) given by [16] as the degree distribution

$$p(i)=\lambda \cdot f(i)+(1\text{-}\lambda)\cdot \mu''(i), \quad for \;\; 1\leq i\leq {}^{k}\!/_{2} \tag{3}$$

where λ, $f(i)$ and $\mu''(i)$ are given in [16]. Symbol $p(i)$ represents the probability of degree at each source, λ is the probabiliity of XORing operation. Symbols $f(i)$ and $\mu''(i)$ represent respectively the degree distribution of XORing part and direct transmission part at the source. The degree d (number of data packets XORed to generate each encoded packet) of a DLT encoded packet is generated at the source by firstly selecting the degree distribution either $f(i)$ (with probability λ) or $\mu''(i)$ (with probability 1-λ) and then choosing degree d with the selected degree distribution. Next, the source selects d data packets equiprobably to XOR them to generate a DLT encoded packets. 2)Relay-sink: DLT encoded packets are combined at the relay to generate an MLT encoded packet such that the resulting stream follows approximately the Robust Soliton Distribution (RSD) which is the robust degree distribution of LT codes to decode all the data packets and given in [11]. The relay must know which distribution, $f(i)$ or $\mu''(i)$, the degree of each DLT encoded packet it receives is drawn before the operation of XORing or propagating directly. So, the destinations receive a mixture of DLT encoded packets and MLT encoded packets.

The DLT based scheme consists of three steps. The whole process is shown in **Fig. 4**.

Algorithm

```
Input
  RSD parameters (k, ε) and random value: val
Output
  n:Number of received packets   λ: Probability to XOR
While n<k(1+ ε) do
  While val ≤ λ do
    I2V phase :Data delivered from base station to relay vehicles
      DLT encoded packets generation alternatively from k1 or k2 with f(i)
    If Existed=0 do (Number of packets kept at relay)
      DLT encoded packets collection at the relay
    end
    If Existed =1 do
      If two DLT encoded packets generated from the same set do
        One DLT encoded packet random selection and collection at the relay
      end
      If two DLT encoded packets generated from different sets do
        MLT packets (XORed DLT packets) generation
      end
    end
    V2V phase :Data delivered between vehicles
    If Existed =1 and two DLT encoded packets generated from
    different sets do
      Relays multicast the MLT encoded packets to destinations
    else
      No V2V phase
  end
  While val > λ do
    I2V phase : Data delivered from base station to relay vehicles
      DLT encoded packets generation from base station with μ''(i)
    V2V phase : Data delivered between vehicles
      Relays multicast the DLT encoded packets to destinations.
  end
end
  Data packets decoding by destinations
```

Fig. 4. Proposed data dissemination algorithm based on DLT coding technique.

1 Source encoding: A random number between 0 and 1 is chosen to indicate its encoding mode: mode1, XORing (degree distribution is $f(i)$ with probability λ) or mode2, direct transmission (degree distribution is $\mu''(i)$ with probability 1-λ). If the random

number is no greater than λ, the source chooses mode1, otherwise the source chooses mode 2.

(1)If the source chooses mode 1, the sequential DLT encoded packets are alternatively generated from k_1 set and k_2 set based on $f(i)$. For example, the DLT encoded packet is generated from k_1 in this time of mode 1 and next time of mode 1 the DLT encoded packet will be generated from k_2;

(2)If mode 2 is chosen, the source only needs to select d data packets randomly from k data packets to generate a DLT encoded packet based on $\mu''(i)$;

The DLT encoded packets continuously are multicasted to the relays. The transmission stops until ACKs are received from all the relays.

2 Relay encoding and forwarding: Every DLT encoded packet is transmitted through source-relay channels modeled in **Fig. 2**.

(1) If mode1 is chosen and no one DLT encoded packet exists at the relays, the new DLT encoded packet will be kept at the relays;

(2) If mode1 is chosen and the existed DLT encoded packet at the relays is generated from different sets with the new DLT encoded packet, the new DLT encoded packet will be XORed with the existed DLT encoded packet to generate an MLT encoded packet. Then, the relays multicast the MLT encoded packet to the destinations. If the DLT encoded packet, which is generated from the alternative set, is lost at source-relay channels, the next DLT encoded packet may be generated from the same set with the existed packet. Relays select randomly one DLT encoded packet and keep it;

(3) If mode2 is chosen, the relays deliver the encoded packet generated by the source to the destinations directly;

3 Destination Decoding: Assume the relay-sink channels also adopt the model in **Fig. 2**. Once the destination receives enough packets, the decoder adopts the decoder recovery rule in [11] to recover the source data. After all k data packets are decoded at a certain destination, an ACK from this destination is sent back to all the relays. The relay also sends an ACK to the source if it receives all the ACKs from each destination.

In addition to the operational details of the scheme mentioned above, we consider the simplified network in **Fig. 3**. We assume that all the nodes operate in half duplex mode. We also assume that the packets are diverse after XORing operation and the packets transmitted directly are the same received by R_1 and R_2. The detailed description of the protocol showing the transmitting nodes, their channel assignments (time slots) and the respective transmitted messages are shown in **Table 3**.

Table 3. Protocol description of DLT based scheme

Time slot	Transmitter	Message	Receiver	Note
1	S	DLT code	R_1 and R_2	S to R
XOR mode ($val \le \lambda$)				
2	S	DLT code	R_1 and R_2	At least one DLT code kept at R_1 or R_2
3	R_1 or R_2	MLT code	D_1 and D_2	At least one DLT code kept at R_1 or R_2 and from different sets

Direct transmission mode ($val>\lambda$)				
2	R_1 and R_2	DLT code	D_1 and D_2	R to D

4. Improved Transmission Scheme: MDLT Based Scheme

This section presents an improved transmission scheme which, in contrast to the approach proposed in Section 3, achieves a better performance on transmission latency and FER for erasure channels. Consider the degree distribution DSD in (3), λ has an important influence on the transmission latency. This is because λ determines the probability of the event whether relays transmit the DLT code directly to the destinations or wait two DLT codes to generate an MLT code.

To address this issue, we develop an improved decomposition technique of the RSD that yields a new degree distribution to be used at the source, called the Modified Deconvolved Soliton Distribution (MDSD). This new degree distribution guarantees a smaller λ which means the directly transmission is more chosen.

4.1 The Modified Deconvolved Soliton

Our decomposition approach is based on the approach in [16] and we will express the RSD as a mixture of two component distributions, where one of the two component distribution is deconvolved as the probability of XORing operation and the other component is represented as the probability of the direct transmission. We derive the modified degree distribution based on the DSD. To reduce transmission latency, our goal is to reduce the XORing event and then increase the direct transmission event in the DSD. Although the details of how to derive the DSD is out of the scope of our discussion, it is still worth going through some of the key aspects. The DSD first splits the RSD $\mu(i)$ into two distribution, $\mu'(i)$ and $\mu''(i)$ [16], such that $\mu'(i)$ is a smooth distribution which is easier to be deconvolved to generate the degree distribution $f(i)$ in (3). The distribution $\mu''(i)$ captures the special part of the RSD, i.e., the degree-one packet and the spike at $i=k/S$. Symbols $\mu'(i)$ in (4) and $\mu''(i)$ in (5) represent respectively XORing and direct transmission part of the RSD, which can be expressed as

$$\mu'(i)=\begin{cases}0, & i=1\\ \left(\rho(i)+\tau(i)\right)/\beta', & 2\le i\le k/S\text{-}1\\ \rho(i)/\beta', & k/S\le i\le k\end{cases} \tag{4}$$

$$\mu''(i)=\begin{cases}\left(\rho(i)+\tau(i)\right)/\beta'', & i=1\\ \tau(\frac{k}{S})\Big/\beta'', & i=k/S\\ 0, & others\end{cases} \tag{5}$$

Here, β' and β'' are given by [16] as follows

$$\beta'=\sum_{i=2}^{k}\rho(i)+\sum_{i=2}^{\frac{k}{S}\text{-}1}\tau(\mathrm{i}) \tag{6}$$

$$\beta''=\rho(1)+\tau(1)+\tau(\frac{k}{S}) \tag{7}$$

And noting that

$$\beta=\beta'+\beta'' \tag{8}$$

Symbols $\rho(i)$ and $\tau(i)$ are given by [11] and expressed respectively as

$$\rho(i)=\begin{cases} 1/k, & i=1 \\ 1/\big(i(i-1)\big), & i=2,\dots,k \end{cases} \tag{9}$$

$$\tau(i)=\begin{cases} S/ik & i=1,\dots,k/S-1 \\ S\ln(S/\delta)/k & i=k/S \\ 0 & others \end{cases} \tag{10}$$

The parameter S represents the average number of degree one packet, defined as

$$S=c\ln(k/\delta)\sqrt{k} \tag{11}$$

where, constants $c>0$ and $\delta\in[0,1]$ given by [11]. Then the RSD $\mu(\text{i})$ is expressed as a mixture of $\mu'(i)$ and $\mu''(i)$ shown as

$$\mu(i)=\frac{\beta'}{\beta}\cdot\mu'(i)+\frac{\beta''}{\beta}\cdot\mu''(i), \quad for\ 1\le i\le\frac{k}{2} \tag{12}$$

Symbols $\mu'(i)$ and $\mu''(i)$ represent respectively the degree distribution of XORing and directly transmission component of RSD in the traditional decomposition technique. Ratios β'/β and β''/β represent the percentage of $\mu'(i)$ and $\mu''(i)$, respectively. To reduce transmission latency, our decomposition approach continues splitting $\mu'(i)$ into two parts: event E_1, the relays forward the packet to the destination directly and event E_2, the relays need XORing operation. So, some points belonged to the XORing event before become a part of the direct transmission event. Then we have the probabilities of event E_1 and event E_2 when the degree is i, which are expressed as

$$P(E_1|d=i)=\begin{cases} 2\cdot\binom{k/2}{i}\Big/\binom{k}{i}, & 1\le i\le k/2 \\ 0, & k/2+1\le i\le k \end{cases} \tag{13}$$

$$P(E_2|d=i)=1\text{-}P(E_1|d=i), \quad 1\le i\le k \tag{14}$$

where d is the degree and k is the number of data packets. Applying Bayes' rule for $1\le i\le k$ yields

$$P(d=i|E_1)=\frac{P(E_1|d=i)\cdot\mu'(i)}{P(E_1)} \tag{15}$$

$$P(d=i|E_2)=\frac{P(E_2|d=i)\cdot\mu'(i)}{P(E_2)} \tag{16}$$

$$P(E_1)=\sum_{i'=1}^{k}P(E_1|d=i')\cdot\mu'(i') \tag{17}$$

$$P(E_2)=1\text{-}P(E_1) \tag{18}$$

Note that $P(d=i|E_1)>0$ if and only if $1\le i\le k/2$ while $P(d=i|E_2)>0$ if and only if $2\le i\le k/2$.

Define $\eta = P(E_1)$, then the degree distribution $\mu'(i)$ can be rewritten as

$$\mu'(i) = \eta \cdot P(d=i|E_1) + (1-\eta) \cdot P(d=i|E_2) \quad (19)$$

Inserting (19) into (12), we have

$$\begin{aligned} \mu(i) &= \frac{\beta'}{\beta} \cdot \mu'(i) + \frac{\beta''}{\beta} \cdot \mu''(i) \\ &= \frac{\beta'}{\beta} \cdot \mu'(i) + (1-\frac{\beta'}{\beta}) \cdot \mu''(i) \\ &= \frac{\beta'}{\beta} \cdot [\eta \cdot P(d=i|E_1) + (1-\eta) \cdot P(d=i|E_2)] + (1-\frac{\beta'}{\beta}) \cdot \mu''(i), \ for\ 1 \le i \le k \end{aligned} \quad (20)$$

which can be rewritten as

$$\mu(i) = \underbrace{\frac{\beta'}{\beta} \cdot (1-\eta) \cdot P(d=i|E_2)}_{XOR} + \underbrace{\frac{\beta'}{\beta} \cdot \eta \cdot P(d=i|E_1) + (1-\frac{\beta'}{\beta}) \cdot \mu''(i)}_{direct\ transmission}, \ for\ 1 \le i \le k \quad (21)$$

We define the total degree distribution of direct transmission as $\mu_1'(i)$ in our technique which contains the direct transmission part $\mu''(i)$ in the DSD and event E_1. We also define the total degree distribution of the XORing operation as $\mu_2'(i)$, which stands for event E2 and is just a part of $\mu'(i)$. So, we can express (21) as

$$\mu(i) = \frac{\beta'}{\beta} \cdot (1-\eta) \cdot \mu_2'(i) + (1-\frac{\beta'}{\beta} \cdot (1-\eta)) \cdot \mu_1'(i) \quad (22)$$

where

$$\mu_1'(i) = \frac{\frac{\beta'}{\beta} \cdot \eta}{1-\frac{\beta'}{\beta} \cdot (1-\eta)} \cdot P(d=i|E_1) + \frac{1-\frac{\beta'}{\beta}}{1-\frac{\beta'}{\beta} \cdot (1-\eta)} \cdot \mu''(i) \quad \text{and} \quad \mu_2'(i) = P(d=i|E_2)$$

As noted above, $\mu_2'(i)$ reflects the degree distribution of code from both k_1 and k_2, so we just need the deconvolution of $\mu_2'(i)$ through polynomial decomposition, which results in the following distribution:

$$f_m(i) = \begin{cases} \sqrt{\mu_2'(2)}, & i = 1 \\ \dfrac{\mu_2'(i+1) - \sum_{j=2}^{i-1} f_m(j) f_m(i+1-j)}{2 f_m(1)}, & 2 \le i \le k/2 \\ 0, & others \end{cases} \quad (23)$$

We now define a new distribution derived by mixing $f_m(i)$ and $\mu_1'(i)$.

Definition 1: The modified deconvolved soliton distribution (MDSD) $p_m(i)$ is given by

$$p_m(i) = \lambda_m \cdot f_m(i) + (1-\lambda_m) \cdot \mu_1'(i), \quad for 1 \le i \le \frac{k}{2} \quad (24)$$

with the parameter λ_m given by $\lambda_m = \sqrt{\frac{\beta'}{\beta}\cdot(1\text{-}\eta)} = \lambda\cdot\sqrt{(1\text{-}\eta)}$

A comparison of the DSD (3), the MDSD (24) and the RSD given by [11] is shown in **Fig. 5** for k=2000. As shown in **Fig. 5**, the MDSD represents for the RSD better than the DSD. The small difference is generated, because the RSD introduced by Luby is robust [11], while DSD and MDSD are both similar to RSD, which endeavour to reconstruct the RSD. We can see that modified λ_m is smaller than original λ, which indicates that it is more easy to chose directly transmission so that MDLT scheme can reduce the transmission latency compared with the DLT scheme.

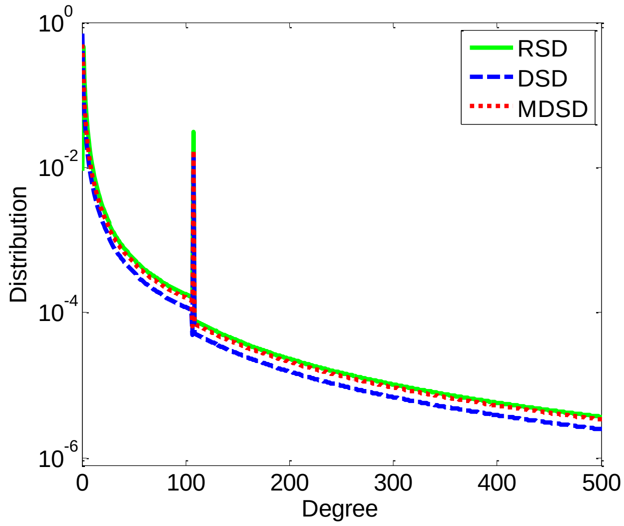

Fig. 5. Degree distribution with support over degrees 1 through 2000.

4.2 Distributed Encoding with MDSD

This subsection addresses how the MDSD can be used to encode packets in the network of **Fig. 1** such that the codes received by the destinations follow approximately the RSD in degree. The distributed encoding algorithm of DLT codes with the MDSD called MDLT scheme, which is similar to our approach in subsection 3.2. Here we use the MDSD instead of DSD as the degree distribution. Distributions $f(i)$ and $\mu''(i)$, two components of the DSD, are now replaced by the components $f_m(i)$ and $\mu_1'(i)$ of the MDSD, respectively.

The process of MDLT based scheme is similar to the algorithm shown in **Fig. 4** except for some slight changes. In the source encoding step, the random number for every received source packets decides which distribution, $f_m(i)$ or $\mu_1'(i)$, is chosen and the probabilities of XORing operation and direct transmission are λ_m and 1-λ_m respectively. The relay encoding and forwarding step and destination decoding step are similar to the transmission scheme in subsection 3.2.

5. Performance Analysis

In this section, we analyze the transmission latency of the proposed schemes, DLT based scheme and MDLT based scheme compared with traditional schemes, ARQ based scheme and

LT based scheme. Consider the case of **Fig. 3** in which the source-relay channels and the relay-sink channels are erasure channels shown in **Fig. 2**. The transmission latency of the system consists of two parts: the encoded packets transmission time at S-R channels and the transmission time at R-D channels. Considering a total of k source packets, we can express the latency T as:

$$T = T_{SR} \cdot N_{SR} + T_{RD} \cdot N_{RD} \tag{25}$$

where T_{SR} and T_{RD} are the transmission time of each packet at S-R and R-D channels, N_{SR} and N_{RD} are the number of total link transmissions by source and relays.

ARQ based scheme: Whether the packet is received successfully or not, a feedback is necessary. Only when all the destinations receive the packet successfully, the source can deliver the following packet. We can obtain N_{SR} and N_{RD} from (26)-(28).

$$\begin{aligned} &N_{SR}^{ARQ} \cdot P_{01} \cdot P_{02} \cdot [1\text{-}(1\text{-}P_{11})(1\text{-}P_{21})] \cdot [1\text{-}(1\text{-}P_{12})(1\text{-}P_{22})] + \\ &N_{SR}^{ARQ} \cdot P_{01} \cdot (1\text{-}P_{02}) \cdot P_{11} \cdot P_{12} + N_{SR}^{ARQ} \cdot P_{02} \cdot (1\text{-}P_{01}) \cdot P_{21} \cdot P_{22} = k \end{aligned} \tag{26}$$

Using (26), we can get

$$\begin{aligned} N_{SR}^{ARQ} = &\, k / \{P_{01} \cdot P_{02} \cdot [1\text{-}(1\text{-}P_{11})(1\text{-}P_{21})] \cdot [1\text{-}(1\text{-}P_{12})(1\text{-}P_{22})] + \\ &P_{01} \cdot (1\text{-}P_{02}) \cdot P_{11} \cdot P_{12} + P_{02} \cdot (1\text{-}P_{01}) \cdot P_{21} \cdot P_{22}\} \end{aligned} \tag{27}$$

$$\begin{aligned} N_{RD}^{ARQ} &= N_{SR}^{ARQ} \cdot [1\text{-}(1\text{-}P_{01})(1\text{-}P_{02})] \\ &= k \cdot [1\text{-}(1\text{-}P_{01})(1\text{-}P_{02})] / \{P_{01} \cdot P_{02} \cdot [1\text{-}(1\text{-}P_{11})(1\text{-}P_{21})] \cdot [1\text{-}(1\text{-}P_{12})(1\text{-}P_{22})] + \\ &\quad P_{01} \cdot (1\text{-}P_{02}) \cdot P_{11} \cdot P_{12} + P_{02} \cdot (1\text{-}P_{01}) \cdot P_{21} \cdot P_{22}\} \end{aligned} \tag{28}$$

So, the total time of ARQ based scheme is

$$T_{ARQ} = N_{SR}^{ARQ} \cdot (T_{SR} + T_{RS}) + N_{RD}^{ARQ} \cdot (T_{RD} + T_{DR}) \tag{29}$$

where N_{SR}^{ARQ} and N_{RD}^{ARQ} are the number of total link transmissions by source and relays in the ARQ based scheme, T_{RS} and T_{DR} stand for the feedback time on S-R and R-D channels respectively. P_{ij} represents the probabilities of good state at L_{ij}.

LT based scheme: All of the relay vehicles need collect and buffer the data messages as long as they enter the radio range of the base station. Because of the high speed mobility of vehicles, relays may not receive enough packets to decode when they are in the radio range of the infrastructure. They deliver the information of the received packets to other relays. Once all the relays receive $k \cdot (1+\varepsilon)$ diverse packets, relay vehicles start to decode and keep encoding LT codes based packets to the destinations until all the destinations send back an ACK. We assume that R_1 and R_2 both receive $k \cdot (1+\varepsilon)/2$ diverse packets when they are within the range of the source S. Symbols $N_{SR_1}^{LT}$ and $N_{SR_2}^{LT}$ are the number of link transmissions by the source to satisfy respectively that R_1 and R_2 receive $k \cdot (1+\varepsilon)/2$ packets. So, we can get

$$N_{SR_1}^{LT} \cdot P_{01} = \frac{k \cdot (1+\varepsilon)}{2} \tag{30}$$

$$N_{SR_2}^{LT} \cdot P_{02} = \frac{k \cdot (1+\varepsilon)}{2} \tag{31}$$

Using (30) and (31), we obtain the number of total transmittions by the source as

$$N_{SR}^{LT} = N_{SR_1}^{LT} + N_{SR_2}^{LT} = \frac{k \cdot (1+\varepsilon)}{2P_{01}} + \frac{k \cdot (1+\varepsilon)}{2P_{02}} \tag{32}$$

When they are out of the range, an extra time $k \cdot (1+\varepsilon) \cdot T_{RR}$ is necessary to communicate between these two relays. Symbol T_{RR} means the transmission time of one packet from one relay to the other relay. We set $N_{RD_1}^{LT}$ and $N_{RD_2}^{LT}$ as number of total link transmissions by the relays to satisfy that D_1 and D_2 receive enough packets to decode respectively. Recoding packets by different relays are diverse, so one destination may achieve two diverse packets in one time slot simultaneously under the condition that all the channels from two relays to itself are good.

To satisfy that both D_1 and D_2 receive $k \cdot (1+\varepsilon)$ packets, we can derive two expressions as follows:

$$N_{RD_1}^{LT} \cdot \left[(1\text{-}P_{11}) \cdot P_{21} + P_{11} \cdot (1\text{-}P_{21}) + 2 \cdot P_{11} \cdot P_{21}\right] = k \cdot (1+\varepsilon) \tag{33}$$

$$N_{RD_2}^{LT} \cdot \left[(1\text{-}P_{12}) \cdot P_{22} + P_{12} \cdot (1\text{-}P_{22}) + 2 \cdot P_{12} \cdot P_{22}\right] = k \cdot (1+\varepsilon) \tag{34}$$

From (33) and (34), we have

$$N_{RD_1}^{LT} = \frac{k \cdot (1+\varepsilon)}{\left[(1\text{-}P_{11}) \cdot P_{21} + P_{11} \cdot (1\text{-}P_{21}) + 2 \cdot P_{11} \cdot P_{21}\right]} \tag{35}$$

$$N_{RD_2}^{LT} = \frac{k \cdot (1+\varepsilon)}{\left[(1\text{-}P_{12}) \cdot P_{22} + P_{12} \cdot (1\text{-}P_{22}) + 2 \cdot P_{12} \cdot P_{22}\right]} \tag{36}$$

$$N_{RD}^{LT} = \max\{N_{RD_1}^{LT}, N_{RD_2}^{LT}\} \tag{37}$$

The total time of LT based scheme is

$$T_{LT} = N_{SR}^{LT} T_{SR} + k \cdot (1+\varepsilon) \cdot T_{RR} + N_{RD}^{LT} \cdot T_{RD} \tag{38}$$

where N_{SR}^{LT} and N_{RD}^{LT} are the number of total link transmissions by source and relays in the LT based scheme. Symbols T_{SR}, T_{RD} and T_{RR} are the transmission time at S-R channel, R-D channel and channels between vehicles, respectively. Symbol P_{ij} represents the probabilities of good state at L_{ij}.

DLT based scheme and MDLT based scheme: We set $N_{SR_1}^{DLT}$ and $N_{SR_2}^{DLT}$ as the number of total link transmissions by the source to satisfy that both D_1 and D_2 receive enough packets, i.e. $k \cdot (1+\varepsilon)$, to decode. We assume two relays multicast the same packet to the destinations if random number $val > \lambda$ and MLT codes from two relays are different after XORing operation. To satisfy that both D_1 and D_2 receive $k \cdot (1+\varepsilon)$ packets, we can derive two expressions as follows:

$$\begin{aligned} &N_{SR_1}^{DLT} \cdot P_{01} \cdot \frac{\lambda}{2} \cdot P_{11} + N_{SR_1}^{DLT} \cdot P_{02} \cdot \frac{\lambda}{2} \cdot P_{21} + \\ &N_{SR_1}^{DLT} \cdot \max\{P_{01} \cdot (1\text{-}\lambda) \cdot P_{11}, P_{02} \cdot (1\text{-}\lambda) \cdot P_{21}\} = k \cdot (1+\varepsilon) \end{aligned} \tag{39}$$

$$\begin{aligned} &N_{SR_2}^{DLT} \cdot P_{01} \cdot \frac{\lambda}{2} \cdot P_{12} + N_{SR_1}^{DLT} \cdot P_{02} \cdot \frac{\lambda}{2} \cdot P_{22} + \\ &N_{SR_2}^{DLT} \cdot \max\{P_{01} \cdot (1\text{-}\lambda) \cdot P_{12}, P_{02} \cdot (1\text{-}\lambda) \cdot P_{22}\} = k \cdot (1+\varepsilon) \end{aligned} \tag{40}$$

From (39) and (40), we have get

$$N_{SR_1}^{DLT} = \frac{k \cdot (1+\varepsilon)}{P_{01} \cdot \frac{\lambda}{2} \cdot P_{11} + P_{02} \cdot \frac{\lambda}{2} \cdot P_{21} + \max\{P_{01} \cdot (1\text{-}\lambda) \cdot P_{11}, P_{02} \cdot (1\text{-}\lambda) \cdot P_{21}\}} \tag{41}$$

$$N_{SR_2}^{DLT}=\frac{k\cdot(1+\varepsilon)}{P_{01}\cdot\frac{\lambda}{2}\cdot P_{12}+P_{02}\cdot\frac{\lambda}{2}\cdot P_{22}+\max\{P_{01}\cdot(1\text{-}\lambda)\cdot P_{12},P_{02}\cdot(1\text{-}\lambda)\cdot P_{22}\}} \tag{42}$$

So the number of total link transmissions at S-R and R-D link are represented respectively as

$$N_{SR}^{DLT}=\max\{N_{SR_1}^{DLT},N_{SR_2}^{DLT}\} \tag{43}$$

$$N_{RD}^{DLT}=N_{SR}^{DLT}\cdot\max\{P_{01}\cdot[(1\text{-}\lambda)+\frac{\lambda}{2}],P_{02}\cdot[(1\text{-}\lambda)+\frac{\lambda}{2}]\} \tag{44}$$

The total time of DLT based scheme is

$$T_{DLT}=N_{SR}^{DLT}T_{SR}+N_{RD}^{DLT}\cdot T_{RD} \tag{45}$$

where N_{SR}^{DLT} and N_{RD}^{DLT} are the number of total link transmissions by source and relays in the DLT based scheme. Symbols T_{SR} and T_{RD} are transmission time at S-R channel and R-D channel.

The calculation method of total transmission time of MDLT based scheme is similar to the DLT based scheme. However, λ in (39)-(45) is now repalced by λ_m.

6. Numerical Simulations

In this section, we describe the main simulation results of the proposed technique. To consider the benefits of using DLT codes in VANETs, we analyze and compare the performance of transmission latency and FER for the I2V2V network as shown in **Fig. 3**. To reduce the influence of randomness and improve accuracy, we use the Monte Carlo simulations to do a large number of simulations. The results are presented for four schemes: ARQ based scheme, LT based scheme, DLT based scheme and MDLT based scheme.

6.1 Transmission Latency

The base station transmits k=64 packets to every vehicle crossing their radio coverage. Assume T_{SR}=T_{RS}=1(time slot), T_{RD}=T_{DR}=1 (time slot) and T_{RR}=2 (time slot) and assume 1 time slot=1seconds. We also assume that RSD parameters are (c, δ)=(0.05,0.5) and all the channels have the same model with p_{ij}=p and q_{ij}=q for the above schemes. RSD parameters c and δ influence the least number of packets received by the destination to begin decoding process and δ is the allowable failure probability of decoding. Based on the RSD parameters and RSD definition, we can obtain ε=0.17. That means once the destination receives n=k(1+ε)=75 packets, the decoder can recover the source packets with probability at least 1-δ. With the analytical results in (29), (38) and (45), we can compute the transmission latency for all four schemes with respect to different p, q and erasure rates. We can obtain the simulation results with different p, q and erasure rates as shown in **Fig. 6**, **Fig. 7** and **Fig. 8** respectively.

As shown in **Fig. 6**, where the latency value is shown in terms of p and q=0.85, MDLT based scheme requires the shortest transmission latency. As p increases, the latency increases significantly for all four schemes. This indicates that if the channel condition is easy to change bad, long transmission latency is needed. DLT based scheme also outperforms the traditional schemes, ARQ based scheme and LT based scheme, with reduced latency. Our proposed DLT based scheme can reduce transmission latency by 41% and 30% respectively, compared with traditional ARQ based scheme and LT based scheme. Moreover, MDLT based scheme can further reduce transmission latency by 25% relative to DLT based scheme. In **Fig. 7**, where the latency is shown in terms of q and p=0.1, MDLT based scheme also requires the shortest latency and the curve drops as the increase of q. That is because the easier the channel state changes to good, the shorter transmission latency is required. Fig.8 shows the transmission latency curves as a function of the erasure rates, from which we can obtain a similar result with Fig.6. Because of the worse channel state, the longer transmission latency is required.

6.2 FER

For a target RSD with parameters k=500, c=0.05 and δ=0.5, we obtain the corresponding DLT distribution DSD and MDSD using (3) and (24). To compare the error performance, we consider LT based scheme, DLT based scheme and MDLT based scheme applied to the two relays and two destinations system in **Fig. 3**. Assume that all the source-relay and relay-sink channels are the model in **Fig. 2** in which each packet is erased with probability P_{SR} and P_{RD}. We assume P_{SR} equals to P_{RD}. In LT scheme, DLT based scheme and MDLT based scheme, the source uses a rate of 1/2 code to the destinations. The resulting FER curves as a function of the erasure rates are shown in **Fig. 9**. As expected, MDLT based scheme outperforms DLT based scheme, because the MDSD is more similar to the RSD than the DSD shown in **Fig. 5**. In addition, compared to the primitive LT code, the performance degrades for both DLT based scheme and MDLT based scheme. The degradation comes from the small difference between the DSD, the MDSD and the RSD. However, the small gap confirms that the DSD and the MDSD are very close to the RSD.

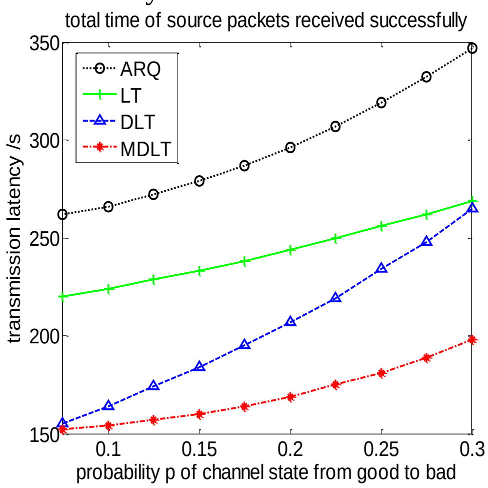

Fig. 6. Comparison of total time of k packets received successfully.

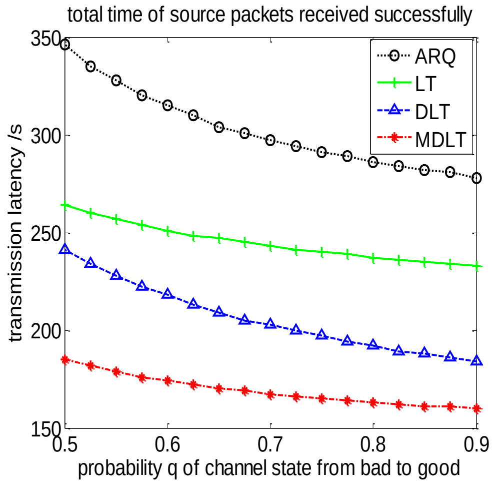

Fig. 7. Comparison of total time of k packets received successfully.

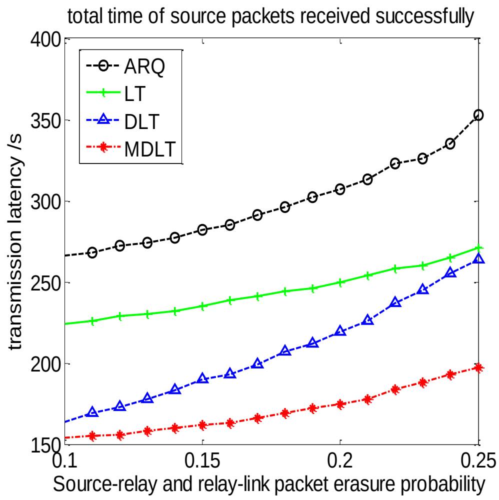

Fig. 8. Comparison of total time of k packets received successfully.

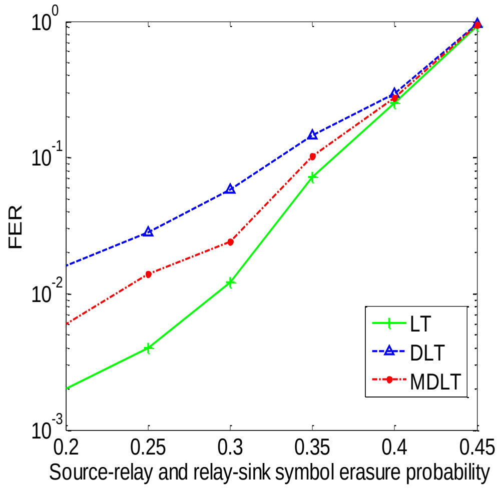

Fig. 9. FER versus erasure probability $p_{SR}=p_{RD}$ $k=500$, $R=1/2$, $n=1000$

As we can see from subsections 6.1 and 6.2, it can be seen that our proposed DLT based and MDLT based schemes reduce the transmission latency compared with the conventional transmission schemes, ARQ based scheme and LT based scheme, at little cost of FER. So our schemes are more adapted to the application scenarios with a critical delay constraint, while a relatively low FER requirement i.e., voice service. We can also conclude that MDLT based scheme requires the shortest latency amoung the four schemes and improves the FER performance compared with DLT based scheme. Thus MDLT based scheme is powerful technique of data delivery for vehicular network where relatively low FER performance is required. Our algorithm exploits the benefit of the most important characteristic of LT codes, i.e. the source data packets can be recovered from any subset of the received packets, once enough packets are received. LT code is applicable for packet-based transmission of mobile multimedia broadcasting channel. The main strengths are more suitable for vehicular environments, where random network topologies and disconnections often occur. So the proposed scheme can be used to provide the broadcast or multicast services via relays in the VANET.

7. Conclusion

In this work, we focus on an I2V2V based vehicular networks, in which there is one source, r relay vehicles and d destination vehicles. We have designed the transmission scheme based on DLT codes to the I2V2V communication. We have further proposed the improved transmission scheme based on the modified degree distribution MDSD. Moreover, the transmission latency of four schemes, ARQ based scheme, LT based scheme, DLT based scheme and MDLT based scheme, was provided. The Monte Carlo simulations confirmed that our proposed DLT based scheme can reduce transmission latency respectively by 41% and 30% compared with traditional ARQ based scheme and LT based scheme, with little cost of FER. MDLT based scheme can further reduce transmission latency by 25% and improve FER performance relative to DLT based scheme.

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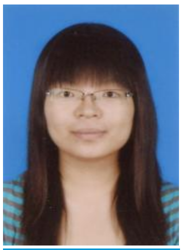

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