Relaying Algorithm Based on Soft Estimated Information for Cooperative V2X Networks

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***Abstract*—With the rapid development of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications (V2X communications), reliable and low-complexity cooperative communication techniques are becoming more and more important due to the requirements of signal reliability and transmission delay for vehicles. Therefore, in this paper, an estimated relaying scheme based on soft information is proposed for cooperative vehicular networks, named by estimate-and-forward (EF) strategy. The proposed EF relay forwards the unconstrained minimum mean square error (MMSE) estimate of the received signal at the relay node (vehicle/infrastructure) to the destination node (vehicle/infrastructure), which outperforms amplify-and-forward (AF) in terms of performance, and achieves lower complexity than decode-and-forward (DF). Therefore, the proposed EF relay achieves a better trade-off between performance and complexity compared to the conventional AF and DF. Simulation results confirm the advantages of the proposed EF for cooperative vehicular networks.**

***Index Terms*—V2X communication, estimate-and-forward, cooperative, vehicular networks**

I. Introduction

Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications (V2X communications) have been paid significant attention because of its increasingly important role in improving traffic safety&efficiency and extending the vision field of a vehicle [1]–[7]. V2X communications system promotes improved intelligent transportation system (ITS) technology for traffic efficiency, safety, management, control and infotainment services. It constructs a communication network between vehicles and vehicles or between vehicles and road(side) infrastructure, and would help to transmit the transport information of real-time traffic states, road information and pedestrian information. Therefore, traffic congestion or obstacles on the road can be detected and relieved, besides, the traffic safety and efficiency can be greatly enhanced. Moreover, the services like digital maps with real-time traffic status and in-car entertainment services offered by V2X communication systems can greatly improve the convenience and comfort of both drivers and passengers, and bring in better user experience with the help of novel parallel intelligent and paralell learning methods [8]–[12].

Nowadays, cooperation communications or information exchanges among vehicles/infrastructure have been a promising way for V2X applications in ITS area [13]–[17]. V2V and V2I communications coexists and cooperates with each other, because V2V communications would become unreliable for multiple-hop communications and V2I communications would be limited by the number of roadside infrastructure. As known, cooperative communication [18] most commonly involves multiple-hop techniques, the basic idea of which is to have one or more intermediate nodes (vehicles or roadside infrastructure) that will repeat or retransmit the signal from one vehicle/infrastructure (transmitter) to another vehicle/infrastructure (destination). These relay channels improve wireless communication performance because of cooperation diversity. That is, the destination receives several copies of the transmit signal, which can be combined to achieve performance improvements such as diversity and multiplexing gains. These gains contribute to achieving decreased transmission powers, low error rate, higher capacity or larger cell coverage.

One key technique of the cooperative relays is the processing of the signal received from the source node. Different relaying schemes result in different system performance [19], [20], which can be categorized generally into amplify-and-forward (AF) and decode-and-forward (DF) relaying schemes. An AF relaying simply scales the received signal and transmits an amplified version to the destination node. Due to its low complexity, the AF relaying is one of the most attractive cooperative diversity schemes. While the absence of a detection process at the relay facilitates with the use of simple relay units, this simple processing enables full spatial diversity at high SNRs [18], [21]. However, the main disadvantage is the performance loss due to the noise amplification at the relay. A DF relaying decodes the received signal, re-encodes, and then retransmits to the receiver. In this case, if the relay makes decoding errors, the errors will propagate

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to the destination. Unlike the AF and DF relaying, estimate-and-forward (EF) [22], as another relay strategy, is thought to be an efficient approach for single antenna uncoded relay networks. Unlike the AF and DF relays, the EF relay computes and transmits an unconstrained minimum mean square error (MMSE) estimate, obtaining an optimized relay function for the whole SNR region. However, EF relaying for cooperative vehicular networks has not been investigated.

Therefore, In this paper, optimized relaying based on soft information for cooperative vehicular networks is developed by extending the main idea of EF. In cooperative V2X communications, the relay vehicle/infrastructure forwards a scaled version of an unconstrained MMSE estimate of the source-transmitted signal. The scaling factor is chosen to satisfy the relay average power constraint. Compared with the conventional AF and DF, the proposed EF achieves a better trade-off between performance and computational complexity in cooperative vehicular networks. In order to further approve the advantages of the proposed EF relaying, different vehicular environments [23] are measured. In this paper, it is assumed that the channel state information is perfectly known or could be perfectly estimated by the receiver [24]–[26]. The corresponding topics with unknown channel state information would be our forthcoming research.

The rest of this paper is organized as follows. Section II introduces the cooperative vehicular communication system and conventional relay methods. Section III describes the proposed relaying algorithm based on soft information. Simulation results and discussions are given in Section IV. Finally, conclusions are drawn in Section V.

II. Background and System Model

The future of communication technology applications in ITS for traffic safety, efficiency, and driving experience relies on cooperative techniques based on V2X communications. Factly, if additional information could be obtained by cooperation with other vehicles and/or with the infrastructure in a continuous and transparent way, it would be of great benefit to vehicular system. Therefore, in this paper, we consider a cooperative vehicular network in support of the IEEE 802.11p wireless access in vehicular environments. The system model is as given in Fig. 1. Any vehicle and/or infrastructure could be the relay node to help to retransmit traffic information.

A. Vehicular Networks

Vehicular networks can be used for traffic safety, traffic management and control, and entertainment information transmission. Some related applications would be activated by the events which have to run every time or are activated just periodically. For example, traffic accident notification, road and traffic conditions, parking availability, commercial applications etc.

In this paper, IEEE 802.11p is considered for the system model, where the modulation is orthogonal frequency division multiplexing (OFDM) at 5.9 GHz with 10 MHz. Vehicles can not transmit and receive at the same time because each

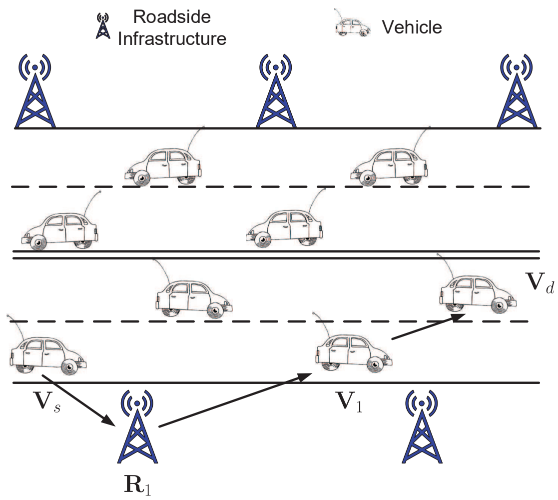

Fig. 1. The system model of cooperative vehicular networks

vehicle is assumed to be equipped with a single antenna. The channels are doubly selective (time-selective and frequency-selective). The vehicular channel model applied in this paper is the standard vehicular channel models based on the IEEE 802.11p standard. The measurement campaign was implemented in the metropolitan Atlanta, Georgia area including three scenarios, i.e., RTV Suburban Street, RTV Expressway, and RTV Urban Canyon. These models only consider multipath fading effects and do not include path loss and lognormal shadowing. Detailed description could be referred to [23].

B. Cooperative Communications

In this section, the cooperative communication strategy is introduced. Generally, the additional constraints posed by limited power and scarce frequency bandwidth make the task of designing high-data-rate&high-reliability wireless communication systems challenging. The challenges of meeting the increasing demands and expectations on wireless communication systems are overwhelming, thus, solutions to enhance wireless performance are necessary. Consequently, cooperation among wireless nodes (vehicles or infrastructure) is possible, which enables relay nodes to forward messages from the source to the destination. Such cooperative relays are being considered for vehicular networks.

In cooperative communications, on the one hand, several independent paths between the source and the destination are created from the relay channels. The relay channels can be thought of as providing auxiliary channels to the direct channel between the source and the destination. These relay channels improve wireless performance due to cooperation diversity. On the other hand, the transmitted power could be saved because of the relaying transmission, and the cell coverage could be enlarged.

A key aspect of the cooperative relays is the processing of the signal received from the source node. Different relaying schemes result in different system performance, which can be categorized generally into AF and DF relaying schemes.

- An AF relaying simply scales the received signal and transmits an amplified version to the destination. Although this relay process amplifies noise, the destination receives multiple versions of the transmitted signal.

- A DF relaying decodes the received signal, re-encodes, and then retransmits to the receiver. In this case, if the relay makes decoding errors, the errors will propagate to the destination.

C. System Model

Throughout this paper, we assume that the channel state information is available at the relay vehicle/infrastructure (node) and the destination node, and it can be, for example, estimated by using the transmitted pilot symbols [24]. Single-relay vehicular networks are investigated in this paper. Our simulation results will be discussed in Section IV.

The system model based on IEEE 802.11p standard is introduced including system transmitter and receiver. The IEEE 802.11p PHY layer is based on OFDM technique, and it has similar structure to that of the IEEE 802.11a except the doubled symbol duration. At the transmitter, convolutional encoder is employed for forward error correction, and higher data rate could be achieved by puncturing. The coded data is then interleaved for mitigating burst errors caused by channel noises. After that, the transmitted signal is modulated, such as BPSK, QPSK, 16 QAM or 64 QAM, and then 64-point inverse fast Fourier transform (IFFT) realizes OFDM. For the 64 OFDM, there are 48 data subcarriers and 4 phase tracking pilot subcarriers, which are located on subcarriers -21, -7, 7, and 21, respectively. At the receiver, the process is the reverse of the transmitter, which would be omitted in this paper.

In this network, the data signals from the source node to the destination node via one relay node. The received signal $\mathbf{r}$ at the relay can be given as

$$r = hx + n_1, \tag{1}$$

where h denotes the channel state information between the source and the relay; and $n_1 \sim \mathcal{CN}(0, \sigma_1^2)$ is an AWGN with variance σ_1^2 and mean 0. x denotes the transmitted signal. It is also assumed that each transmitted symbol is chosen from the same constellation; i.e., $x \in \mathcal{Q}$, and $\mathcal{E}[\|x\|^2] = P_s$ is the average transmitted power, where P_s denotes the source power and $\mathcal{E}(x)$ means the expectation of x.

A memoryless relay receives the source signal from the source, generates and transmits the processed signal to the destination, and its relay function $\mathcal{G}(r)$ uses the received signal r at the relay node. The assumption is that the average relay power P_r of the transmitted signal $\mathcal{G}(r)$ is constrained by $\mathcal{E}[\|\mathcal{G}(r)\|^2] = P_r$. Therefore, after this relay retransmits their processed signals, the received signal at the destination could be written as

$$y = g\mathcal{G}(r) + n_2, \tag{2}$$

where g denotes the channel between the relay and the destination, and $n_2 \sim \mathcal{CN}(0, \sigma_2^2)$ is the AWGN noise with mean 0 and variance σ_2^2.

The performance of memoryless relay networks depends critically on the relay function, which have been studied in [19], [20]. It is assumed that the channel information h and g is perfectly known by the receiver, or could be perfectly estimated [26]. The two conventional relay functions of memoryless forwarding strategies (AF and DF relaying) for relay networks are discussed next.

1) Amplify-and-Forward: Among the conventional relay strategies, AF relaying is the most basic relay strategy. For each transmit symbol, the relay retransmits a amplified/scaled version of the received signal to the destination. Thus, a linear relay function is used. Furthermore, to satisfy the average power constraint, the AF relay function can be given as

$$\mathcal{G}_{AF}(r) = \alpha r = \sqrt{\frac{P_r}{\mathcal{E}[\|h\|^2]P_s + \sigma_1^2}}\, r, \tag{3}$$

where α is the scaling factor, and r is derived by (1); P_s and P_r are the source and the relay average power levels, respectively. Then, the scaled version of the received signal is sent to the destination.

Due to its low complexity, the AF relaying is one of the most attractive cooperative forwarding schemes. While the absence of a detection process at the relay facilitates with the use of simple relay units, this simple processing enables full spatial diversity at high SNRs [18], [21]. However, the main disadvantage is the performance loss due to the noise amplification at the relay when amplifying the transmitted signal.

2) Decode-and-Forward: The DF relay method has attracted much attention recently because it outperforms AF in terms of bit error rate (BER). It firstly detects data from the incoming signal, then remodulates and forwards them to the destination. This method may use an maximum-likelihood (ML) detection of data from the incoming signal. The detected signal may be given as

$$\hat{x} = \arg\min_{x \in \mathcal{Q}} \|r - hx\|^2, \tag{4}$$

where $\arg\min_x f(x)$ denotes the value of x that minimizes $f(x)$.

Although $\hat{x}$ can be directly transmitted, the relay power constraints still need to be satisfied. Thus, the DF relay function could be given as

$$\mathcal{G}_{DF}(r) = \sqrt{\frac{P_r}{\mathcal{E}(\|\hat{x}\|^2)}}\hat{x} = \sqrt{\frac{P_r}{P_s}}\hat{x}. \tag{5}$$

However, once the source-relay link suffers from deep fading, the decoding errors at the relay will also propagate to the destination.

III. Proposed Relaying based on Soft Information

In this section, we propose the EF relay based on soft information for cooperative vehicular networks. Unlike AF and DF relay, which transmit the amplified version and the hard decisions, respectively, the EF relay transmits estimated soft information as shown in Fig. 2. The soft information which helps data detection at the destination is a scaled unconstrained MMSE estimate of the transmitted signal x at the relay.

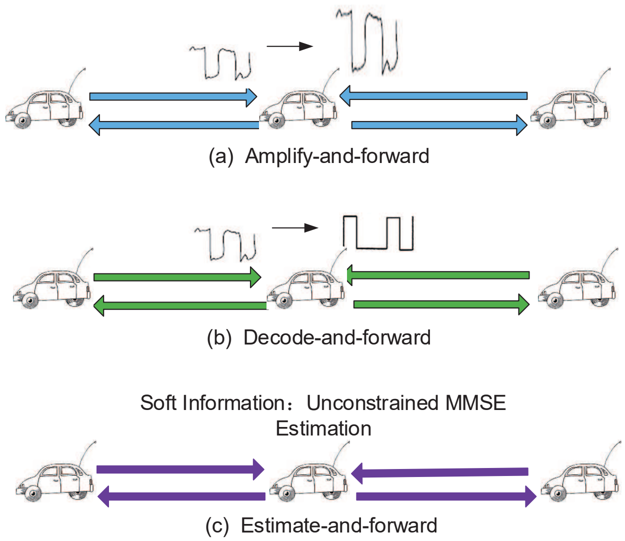

Fig. 2. Three relaying methods for cooperative vehicular networks

A. Estimate-and-Forward

The unconstrained MMSE estimate is the conditional mean of x, given the received signal r and channel state information h, and it can be stated as

$$\hat{x} = \mathcal{E}(x|r,h) = \frac{\sum_{x\in\mathcal{Q}} x f(r|x,h)P(x)}{\sum_{x\in\mathcal{Q}} f(r|x,h)P(x)}, \tag{6}$$

where $P(x)$ denotes the priori probability of the transmitted signal x, and $f(r|x,h)$ denotes the probability density function (PDF) of r conditional on x and h. Because the addition noise vector is independent and identically distributed (i.i.d) Gaussian, the PDF $f(r|x,h)$ may be written as

$$f(r|x,h) = \frac{1}{\pi\sigma_1^2}\exp\left(-\frac{\|r-hx\|^2}{\sigma_1^2}\right). \tag{7}$$

Assuming equal priori probabilities for all transmitted symbols, the EF relaying computes the MMSE estimate as

$$\hat{x} = \frac{\sum_{x\in\mathcal{Q}} x\exp\left(-\frac{\|r-hx\|^2}{\sigma_1^2}\right)}{\sum_{x\in\mathcal{Q}}\exp\left(-\frac{\|r-hx\|^2}{\sigma_1^2}\right)}. \tag{8}$$

To satisfy the relay power constraint, the scaling factor for EF relaying, like that for AF and DF relaying, is given by

$$\beta = \sqrt{\frac{P_r}{\mathcal{E}(\|\hat{x}\|^2)}} = \sqrt{\frac{P_r}{\int_{-\infty}^{\infty}\|\hat{x}(r)\|^2 f(r)dr}}. \tag{9}$$

By using the total probability law, the PDF of received signal r can be obtained as

$$\begin{aligned} f(r) &= \sum_{x\in\mathcal{Q}} f(r|x,h)P(x) \\ &= \sum_{x\in\mathcal{Q}}\frac{1}{\pi\sigma_1^2}\exp\left(-\frac{\|r-hx\|^2}{\sigma_1^2}\right)\frac{1}{|\mathcal{Q}|}. \end{aligned} \tag{10}$$

Thus, the relay retransmits the scaled version of the MMSE estimate $\beta\hat{\mathbf{x}}$ to the destination. The EF relay function is therefore

$$\mathcal{G}_{EF}(r) = \sqrt{\frac{P_r}{\int_{-\infty}^{\infty}\|\hat{x}\|^2 f(r)dr}} \times \frac{\sum_{x\in\mathcal{Q}} x\exp\left(-\frac{\|r-hx\|^2}{\sigma_1^2}\right)}{\sum_{x\in\mathcal{Q}}\exp\left(-\frac{\|r-hx\|^2}{\sigma_1^2}\right)}. \tag{11}$$

B. Analysis of EF Performance

In this subsection, Theoretical analysis for the performance of the proposed EF is discussed. For simplification, it is assumed that the constellation is symmetric, that is to say, $x\in\mathcal{Q} \Leftrightarrow -x\in\mathcal{Q}$.

In low SNR region, when the receive SNR at the relay node is very low, the MMSE estimate can be derived as

$$\begin{aligned} \lim_{\sigma_1^2\to\infty}\hat{r} &= \lim_{\sigma_1^2\to\infty}\frac{\sum_{x\in\mathcal{Q}} x\exp\left(-\frac{\|r-x\|^2}{\sigma_1^2}\right)}{\sum_{x\in\mathcal{Q}}\exp\left(-\frac{\|r-x\|^2}{\sigma_1^2}\right)} \\ &= \lim_{\sigma_1^2\to\infty}\frac{\sum_{x\in\mathcal{Q}} x\exp\left(-\frac{-x^Hr-r^Hx+x^Hx}{\sigma_1^2}\right)}{\sum_{x\in\mathcal{Q}}\exp\left(-\frac{-x^Hr-r^Hx+x^Hx}{\sigma_1^2}\right)} \end{aligned} \tag{12}$$

Because the constellation is symmetric, if $f(x)$ is an even function in x, thus $\sum xf(x) = 0$. Therefore, the above equality is derived as

$$\lim_{\sigma_1^2\to\infty}\hat{x} = \lim_{\sigma_1^2\to\infty}\frac{\sum_{x\in\mathcal{Q}} x\left(1-\frac{-x^Hr-r^Hx+x^Hx}{\sigma_1^2}\right)}{\sum_{x\in\mathcal{Q}}\left(1-\frac{-x^Hr-r^Hx+x^Hx}{\sigma_1^2}\right)}$$

Furthermore, it is known that $\lim_{\sigma^2\to\infty} n/\sigma_1^2 = 0$ with probability 1 and $\lim_{x\to 0} e^x = \lim_{x\to 0} 1+x$, thus it is derived as

$$\begin{aligned} \lim_{\sigma_1^2\to\infty}\hat{x} &= \lim_{\sigma_1^2\to\infty}\frac{\sum_{x\in\mathcal{Q}} x\frac{x^Hr+r^Hx}{\sigma_1^2}}{|\mathcal{Q}|-\sum_{x\in\mathcal{Q}}\frac{x^Hx}{\sigma_1^2}} \\ &= \frac{1}{\sigma_1^2|\mathcal{Q}|}\left(\left(\sum_{x\in\mathcal{Q}} xx^H\right)r + \left(\sum_{x\in\mathcal{Q}} xx^T\right)r^*\right) \end{aligned} \tag{13}$$

By analyzing Eq. (13), it could be found that the proposed EF converges to an alike AF relaying in the low SNR region. This deduction can be further simplified for different constellations.

In high SNR region, the ML detection decision is denoted by x_{ML}; thus, the unconstrained MMSE estimate is given by

$$\begin{aligned} \lim_{\sigma_1^2\to 0}\hat{x} &= \lim_{\sigma_1^2\to 0}\frac{\sum_{x\in\mathcal{Q}} x\exp\left(-\frac{\|r-x\|^2}{\sigma_1^2}\right)}{\sum_{x\in\mathcal{Q}}\exp\left(-\frac{\|r-x\|^2}{\sigma_1^2}\right)} \\ &= \lim_{\sigma_1^2\to 0}\frac{x_{ML}\exp\left(-\frac{\|r-x_{ML}\|^2}{\sigma_1^2}\right)+\sum_{x\in\tilde{\mathcal{Q}}} x\exp\left(-\frac{\|r-x\|^2}{\sigma_1^2}\right)}{\exp\left(-\frac{\|r-x_{ML}\|^2}{\sigma_1^2}\right)+\sum_{x\in\tilde{\mathcal{Q}}}\exp\left(-\frac{\|r-x\|^2}{\sigma^2}\right)} \\ &= \lim_{\sigma_1^2\to 0}\frac{x_{ML}+\sum_{x\in\tilde{\mathcal{Q}}} x\exp\left(-\frac{\|r-x\|^2-\|r-x_{ML}\|^2}{\sigma^2}\right)}{1+\sum_{x\in\tilde{\mathcal{Q}}}\exp\left(-\frac{\|r-x\|^2-\|r-x_{ML}\|^2}{\sigma^2}\right)}, \end{aligned} \tag{14}$$

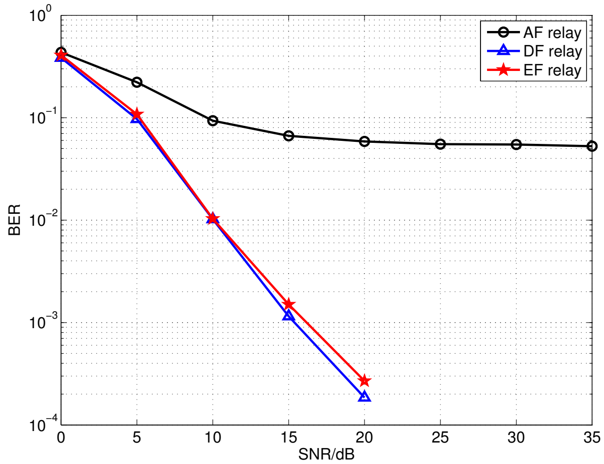

Fig. 3. BER comparison for different relaying methods in RTV-Expressway Channel with Distance = 50m, v = 40km/h.

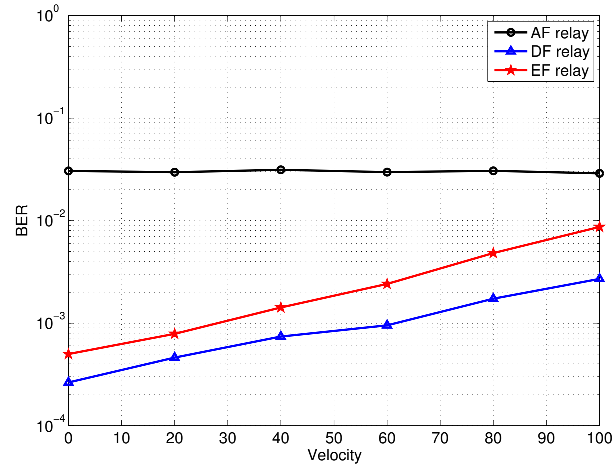

Fig. 4. BER comparison for different vehicle velocity and different relaying methods in RTV-Expressway Channel with Distance = 50m.

where $\tilde{\mathcal{Q}} = \{x \in \mathcal{Q} \text{ except } x_{ML}\}$. For all $x \in \mathcal{Q}$, it is known that $x \neq x_{ML}$; thus, the $\|r - x\|^2 - \|r - x_{ML}\|^2 > 0$. That means, if SNR goes to infinity, it is lower bounded by $\|r - x\|^2 - \|r - x_{ML}\|^2 > 0$ with probability 1. Therefore, it is derived that $\lim_{\sigma^2 \to 0} \exp\left(-\frac{\|r-x\|^2 - \|r-x_{ML}\|^2}{\sigma^2}\right) = 0$. The proposed unconstrained MMSE estimate thus approximates as

$$\lim_{\sigma_1^2 \to 0} \hat{x} \quad = \quad x_{ML}, \tag{15}$$

which approaches DF relaying. Consequently, for high S-NRs in cooperative vehicular networks, EF converges to DF scheme. Therefore, the performance of EF and AF relaying schemes converge in the low-SNR region, while those of EF and DF relaying schemes perform very close in the high SNR region.

IV. Simulation Results

In this section, the performance measured by BER is compared and discussed for the proposed EF, DF, and AF in different vehicular scenarios. It is assumed that the power at the source is equal to that at the relay ($P_s = P_r$), and noise variance between the source node and the relay node is equal to that between the relay and the destination ($\sigma_1^2 = \sigma_2^2$). The code rate of convolutional code is set to be $1/2$. The other related parameters of the system model are based on IEEE 802.11p standard.

Firstly, the BER performance of different relay strategies is given for a QPSK cooperative vehicular network in Fig. 3. The proposed EF algorithm is compared with the classical DF and AF schemes. In this simulation figure, it is assumed that the distance between the source node and the relay node and that between the relay and the destination node are both 50m. Further, RTV-Expressway channel is used here with the velocity $v = 40\,\text{km/h}$. In the low SNR region, for example, $0\,\text{dB}$, these three relay schemes perform almost the same. However, it is clear to find that the proposed EF outperforms AF for high SNRs. Moreover, the BER of the proposed EF approaches that of DF relay for high SNRs, which confirms the analysis in Section III. It is worthy to mention that the proposed EF achieves similar performance with the conventional DF with much low complexity because the EF does not need detection process.

In order to check how the velocity impacts the performance of the proposed EF, AF and DF relays for cooperative vehicular channels, the BER performance for different velocity of these three relay schemes are compared in Fig. 4 with SNR$=15\,\text{dB}$, where the distance is still assumed to be 50m and the channel is chosen to be RTV-Expressway channel. From this figure, we can find that the proposed EF performs better than the conventional AF relay scheme, while it has some performance loss compared to the DF relay scheme. However, the proposed EF relay does not need the complicated ML detection at the relay, while it achieves performance gain compared AF only by soft information computation. Another interesting consequence is that the BER performance of the proposed EF and the conventional DF become worse with increasing vehicle velocity, while AF performs almost the same for different vehicle velocity. Thus, the performance gain of the proposed EF is getting smaller with increasing vehicle velocity comparing with the AF.

The BER performance of the proposed EF for different vehicular channels are further compared to confirm the benefits of the proposed EF algorithm for cooperative vehicular networks. Fig. 5 shows that the BER performance of the proposed EF for RTV-Expressway, RTV-Urban Canyon, and RTV-Suburban channels for different vehicle velocity. From these curves, it is clear that the proposed EF in RTV-Urban Canyon channel achieves the best performance, which achieves more performance gains than that in RTV-Expressway and RTV-Suburban channels. Moreover, it is similar to the results in Fig. 4, the performance for these three vehicular environments all becomes worse when the vehicles moves with increasing velocity.

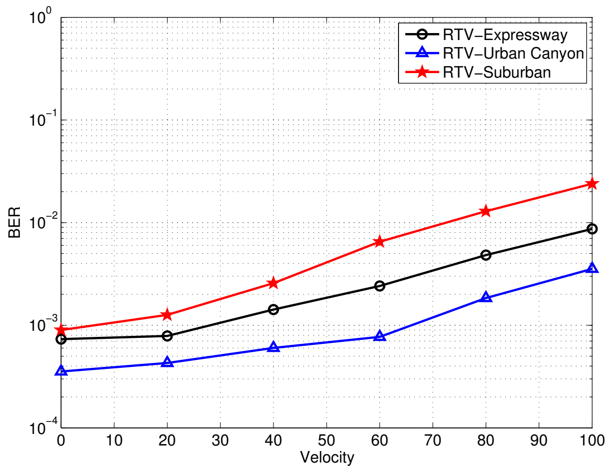

Fig. 5. BER comparison of EF relaying for different vehicular channels.

V. Conclusion

An estimate-and-forward scheme based on soft estimated information was proposed and analyzed for cooperative V2X networks in this paper. Different with the conventional AF and DF, the proposed EF relay forwards the unconstrained MMSE estimate of the received signal from the transmitted vehicle node (vehicle/infrastructure) to the received node (vehicle/infrastructure). Based on the theoretical analysis, the relay node thus achieves clearly better performance than AF, and performs similar to DF with much lower computational complexity. Furthermore, simulation results for different vehicular scenarios further confirmed the advantages of the proposed EF relaying strategy. The EF relaying would be one potential forwarding method for cooperative vehicular networks because of its advantages of the better trade-off between performance and implementation complexity.

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