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CPSS-based Signal Forwarding Method at Relays for Full-duplex Cooperative Vehicular Networks

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***Abstract*— With increasing popularity of Internet of Vehicles (IoV), concerns for reliable and low complexity communication techniques are proposed due to the requirements of signal reliability and transmission delay for vehicles. Meanwhile, the explosive and pervasive use of social network applications further adds drivers' social relationships and behavioural characteristics into it, and makes it a cyber-physical-social system (CPSS). This paper proposes and analyzes an improved forward scheme for full deplex cooperative vehicular networks in terms of its CPSS features. The proposed CPSS-based forwarding (CPSS-F) strategy forwards a soft estimate of the received signal based on social historic data at the relay node (vehicle/infrastructure) to the destination node (vehicle/infrastructure), which achieves improved reliability than the two conventional strategies in cooperative networks, i.e., amplify-and-forward (AF) and decode-and-forward (DF). Furthermore, the proposed CPSS-F relay achieves performance gains and complexity reduction compared to the conventional AF and DF. Experimental results further confirm the advantages of the proposed CPSS-F for cooperative vehicular networks. The proposed CPSS-F approach is easily extended to other cooperative vehicular social networks, for example, multi-way, half-duplex, or large-antenna networks.**

I. INTRODUCTION

Vehicles have brought significant changes over years and will continue to do so in the future. In particular, since drivers can share information and data with their neighbors through social media application, vehicles can be connected into a social network through vehicular communications. Social features and human-centric behaviours play important roles in vehicular networks [1]–[3]. Vehicle-to-anything communications (V2X communications) including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehilce-to-pedestrain (V2P) communications have been paid significant attention due to its increasing importance for traffic safety&efficiency improvement and the vision field extension of a vehicle [4]–[7]. V2X communication systems would greatly support improved intelligent transportation system (ITS) technologies for traffic efficiency, safety, management, control and infotainment services.

A vehicular communication network is constructed between vehicles and vehicles or between vehicles and road(side) infrastructure, and this network would help to transmit/broadcast the transport information of real-time traffic states, road information and pedestrian information. Therefore, traffic congestion or obstacles can be detected and relieved timely. Besides, the traffic efficiency and safety can be enhanced. Moreover, the services, such as in-car entertainment services and digital maps with real-time traffic status offered by V2X communication systems can efficiently improve the comfort and convenience of both drivers and passengers, and bring in better user experience with the help of novel parallel intelligence [8]–[10] and paralell learning methods [11]–[17].

Currently, cooperation communications and information exchanges among vehicles/infrastructures have been a promising way for V2X applications in ITS area [18], [19]. V2X communications coexists and cooperates with each other, where V2V communications would become unreliable for multiple-hop communications and V2I communications would be limited by the number of roadside infrastructures. As we know, cooperative communications [20] is to repeat or retransmit the signal from one vehicle/infrastructure (transmitter) to another vehicle/infrastructure (destination) by the help of one or more intermediate nodes (vehicles or roadside infrastructure). It contributes to achieving low error rate, decreased transmission power, higher capacity or larger cell coverage.

Full-duplex technique has gained much attention and been considered as an important potential technique for 5G systems [21]–[23]. It can achieve lower end-to-end latency and higher link capacity [24]–[27]. The whole communication rate between two transmitters is approximately twice of that achieved rate in half-duplex networks. Thus, the process of the received signal at the relay node becomes one of the key techniques for cooperative networks. The design of relaying schemes directly impacts system performance [28], [29], which mainly includes amplify-and-forward (AF) and decode-and-forward (DF) techniques. AF simply amplifies

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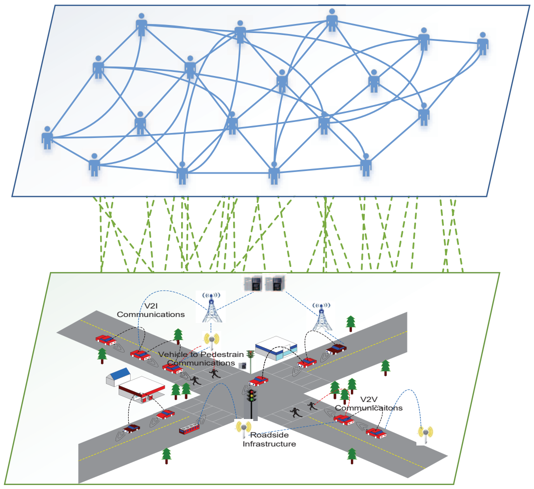

Fig. 1. An illustration of the framework for physical and social networks.

the received signal and retransmits to the destination node. This method achieves low complexity. However, it leads to the performance loss because it also amplifies the noise. Corresponding to AF, DF decodes, re-encodes, and retransmits the processed signal to the destination. However, once decoding errors happened, these errors will be propagated to the destination.

Therefore, in this paper, a cyber-physical-social systems (CPSS)-based forwarding (CPSS-F) strategy is proposed for full-duplex cooperative vehicular network, which follows the main idea of CPSS [10], [30], [31] and parallel vehicular networks. The proposed CPSS-F strategy forwards a soft estimate of the received signal based on social historic data at the relay node to the destination node, which achieves improved reliability than the two general AF and DF methods in cooperative vehicular networks. Furthermore, it obtains a better trade-off between system performance and computational complexity, which is easy for practical implementation. Experimental results further confirm the advantages of the proposed CPSS-F for cooperative vehicular networks. Furthermore, the proposed CPSS-F approach is easily extended to other cooperative vehicular social networks, i.e., multi-way or large-antenna vehicular networks.

II. Parallel Vehicular Networks

A. Vehicular Networks

Internet of Vehicles (IoV) have attracted a large number of companies and researchers because of its huge commercial interests and research value. IoV is the convergence of Internet of Things (IoT) and the mobile Internet. It is comprised of human-driven or automated intelligent vehicles, and is integrated with intelligent perception and V2X communication equipment. Therefore, IoV is a cross-disciplinary technology that encompasses communications, networks, controls, cyber-security and social sciences. Current IoV researches focus on traffic safety and efficiency, low latency information transmission, high reliability, zero handover execution time, etc. IoV technology generally refers to dynamic mobile communication systems that communicate between vehicles and public networks using V2X interactions. These interactions complete information sharing and aggregation from vehicles, road(side) infrastructure and surrounding intelligent equipment. Furthermore, the characteristics of IoV is integrating process, computation, share, and secure for the release of related information through information platforms.

Currently, the rapid development of online social networks has stressed moving vehicles' social relationships (Fig. 1), which conversely led to more data traffic because of the effect of vehicular networks. Vehicular communications could be thought as the social network for vehicles because the drivers, passengers and pedestrians can share information with others. Thus, social features and human behavior have significant impacts on transportation networks. The social IoV concept is an example of the social IoT, which is a network of intelligence objects with social interactions. It is commonly described as social interactions among vehicles that communicate autonomously for services and information exchange. The main part is the vehicle equipped with advanced technological devices, while the vehicles may use the online social network service to share information with others. The vehicular network collects real-time data, and provides the ability to share information among vehicles/pedestrians in different locations. This would combine the multi-modal data from vehicular networks and social networks.

B. Parallel Vehicular Networks

As illustrated in [32], CPSS enables pervasive intelligent space to interact smartly with people and things anywhere and anytime. This is built upon the foundation of pervasive computing, communication, and control. Therefore, based on CPSS system and parallel intelligence, the framework of CPSS-based parallel vehicular networks is illustrated in Fig. 2. PVN becomes an intelligent system when they are capable to observe&prescribe what is happening within the system, construct system models, communicate with internally and externally, act based on the system decisions, and predict&guide the future system status by data analysis. There are two main sub-systems in the proposed PVN, which are physical vehicular network and artificial software-defined vehicular network.

Artificial Software-Defined Vehicular Network: Corresponding to the physical vehicular network (VN), there could be one or several artificial VN systems to model the physical system. An artificial software-defined VN embraces vehicle models, road(side) infrastructure models, information transmission network models, pedestrian models, social network models, etc. Due to different users‘ requirements, the modeling and optimization for VNs will be designed based on the specific needs. The modeling can be designed to maximize a specific target in VNs such as the information dissemination efficiency, the users‘ cooperation degree, the relay success rate, the benefit of resource allocation, and the network architecture. In this paper, we demonstrate the models and the corresponding optimizations based on the

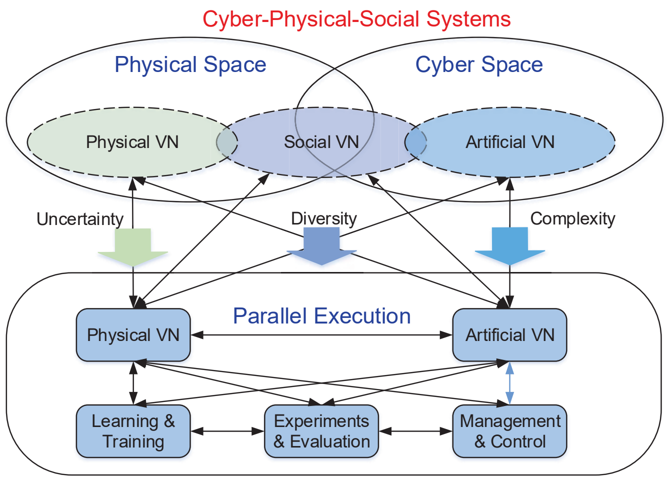

Fig. 2. The framework of parallel vehicular networks.

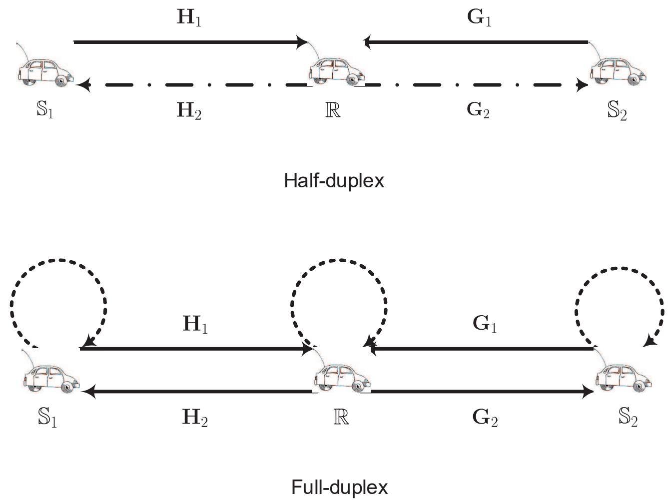

Fig. 3. The system model of half-duplex and full-duplex cooperative vehicular network.

features of full-duplex cooperative VN. This artificial system operates by themselves in Cyberspace, and their operating status and results will be the reference for physical network system deployment.

Computational Experiments: The second important component of parallel intelligence is computational experiments. As known, the sensors of the physical VN includes electronic police, monitoring devices, social network sensors etc., whose tasks are data collection, data uploading, vehicles networking, social networking, and so on. All these modules constitute a multi-modal data vehicular network system. By the analysis on these multi-modal big data, the cyber source could be effectively allocated. For instance, individual recommendation, traffic status prediction, recommended trajectory, and so on. Here, for the individual recommendation, collaborative filtering recommendation algorithm and the key rules recommendation algorithms could be used for specific scenarios. While for the traffic status prediction, there are many kinds of algorithms, for example, neural network, Calman filtering, nonparametric regression model, and so on. It is worthy to mention that the multi-modal big data for computational experiments are derived not only from physical VN system but also from artificial VN system.

Parallel Execution: The main idea of parallel execution between physical and artificial VN system is demonstrated here. For one thing, a variety of experimental or computational results of artificial VN system would provide guidance and prediction for physical VN systems for its optimization. For another, the multi-modal big data from physical VN system would also feedback to artificial VN system for its further adjustment. To achieve further improvement of the operating status for physical system and artificial system, parallel execution approaches would be designed for different requirements, such as network resource control, V2V/V2I network deployment, social network model, cooperative management, etc.

In next section, one application example of PVN is designed, demonstrated and discussed in full-duplex cooperative vehicular network.

III. Full-duplex Cooperative Vehicular Network Model

As shown in Fig. 3, a system model for cooperative vehicular networks is given, where the first vehicle node $\mathbb{S}_1$ is equipped with $N_{S1} \geq 1$ antennas, the relaying vehicle $\mathbb{R}$ has $M_r \geq 1$ transmit antennas and $N_r \geq 1$ receive antennas, and the second vehicle node $\mathbb{S}_2$ is equipped with $N_{S2} \geq 1$ antennas. In this paper, it is assumed that only one relay $\mathbb{R}$ is in the cooperative vehicular network and terminals $\mathbb{S}_1$ and $\mathbb{S}_2$ interact information with each other by this relay node. As shown in Fig. 3, for half-duplex system, the transmission and reception of information must happen alternately. While one node is transmitting, the other must only receive. However, full-duplex communication between two nodes means that both of them can transmit and receive information between each other simultaneously.

Firstly, both the vehicle node $\mathbb{S}_1$ and $\mathbb{S}_2$ send out signals $\mathbf{s}_1$ and $\mathbf{s}_2$ to the relaying vehicle node. The received signal can be derived by

$$\tilde{\mathbf{R}} = \mathbf{H}_1\mathbf{s}_1 + \mathbf{G}_1\mathbf{s}_2 + \mathbf{H}_R\mathbf{s}_R + \mathbf{n}, \tag{1}$$

where $\mathbf{s}_R$ represents the signal transmitted from the relaying vehicle node, and $\mathbf{H}_R$ is the loop channel state information (CSI) at the relaying node; The CSI between $\mathbb{S}_1$ and $\mathbb{R}$ and between $\mathbb{R}$ and $\mathbb{S}_2$ are defined to be $\mathbf{H}_1 = [h_{ij}] \in \mathcal{C}^{N_r \times N_{S1}}$ and $\mathbf{G}_1 = [h_{ij}] \in \mathcal{C}^{N_r \times N_{S2}}$, respectively. The elements of $\mathbf{H}_1$ and $\mathbf{G}_1$ are assumed to be independent identically distributed (i.i.d.) complex Gaussian ($h_{ij}, g_{ij} \sim \mathcal{CN}(0,1)$); $\mathbf{n} = [n_1, n_2, \ldots n_{N_r}]^T$ and $n_i \sim \mathcal{CN}(0, \sigma^2)$ ($i = 1, 2, \ldots, N_r$) is an additive white Gaussian noise (AWGN) (mean 0 and variance σ^2); $\mathbf{s}_1 = [s_{11}, s_{12}, \ldots, s_{1N_{S1}}]^T$ and $\mathbf{s}_2 = [s_{21}, s_{22}, \ldots, s_{2N_{S2}}]^T$ denote the transmitted signal at $\mathbb{S}_1$ and $\mathbb{S}_2$, respectively. The constellation method is defined to be $\mathcal{Q}$, i.e., $s_{ij} \in \mathcal{Q}$ ($i = 1, 2$), and $\mathcal{E}[\|\mathbf{s_i}\|^2] = P_t$, where $\mathcal{E}(s)$ is the expectation of s and P_t is the transmitted power.

At the relaying vehicle node, it processes and transmits the received signal to the other node $\mathbb{S}_2$ and $\mathbb{S}_1$. In this paper, it is assumed that the relay node has full knowledge of the loop interference channel and the transmitted signal by itself; Consequently, the received signal is given as

$$\mathbf{R} = \mathbf{H}_1\mathbf{s}_1 + \mathbf{G}_1\mathbf{s}_2 + \mathbf{n}. \tag{2}$$

After that, with the assumption of the relay average power P_R, the transmitted signal $\mathcal{F}(\mathbf{R})$ should be constrained by $\mathcal{E}[\|\mathcal{F}(\mathbf{R})\|^2] = P_R$. Further, the signal from the loop channel at $\mathbb{S}_1$ and $\mathbb{S}_2$ is assumed to be perfectly known and removed. Thus, after the processed signals are retransmitted, the received signal at $\mathbb{S}_1$ and $\mathbb{S}_2$ can be derived as

$$\mathbf{y}_1 = \mathbf{H}_2\mathcal{F}(\mathbf{R}) + \mathbf{n_1}, \tag{3}$$

and

$$\mathbf{y}_2 = \mathbf{G}_2\mathcal{F}(\mathbf{R}) + \mathbf{n_2}, \tag{4}$$

respectively, where $\mathbf{H}_2 = [h_{ij}] \in \mathcal{C}^{N_{S1}\times M_r}$ and $\mathbf{G}_2 = [g_{ij}] \in \mathcal{C}^{N_{S2}\times M_r}$ denote the MIMO channel between $\mathbb{R}$ and $\mathbb{S}_1$ and between $\mathbb{R}$ and $\mathbb{S}_2$, respectively. The elements of $\mathbf{H}_2$ and $\mathbf{G}_2$ are also i.i.d. complex Gaussian; and $\mathbf{n_1} = [n_{11}, n_{12}, \ldots n_{1N_{S1}}]^T$ and $\mathbf{n_2} = [n_{21}, n_{22}, \ldots n_{2N_{S2}}]^T$ ($n_{ij} \sim \mathcal{CN}(0, \sigma_i^2)$, where $i = 1, 2$ and $j = 1, 2, \ldots, N_{Si}$).

In this paper, it is assumed that the CSI is perfectly known at the relay and the two transmit vehicle nodes. Furthermore, for simplicity, only one relay vehicle scenario is considered in the full-duplex cooperative vehicular network. However, the extension to include multiple relay nodes is straightforward but omitted in this paper due to space limitation.

IV. CPSS-based Forwarding Method

As known, there exists two general forwarding methods for cooperative vehicular networks, i.e., decode-and-forward (DF) and amplify-and-forward (AF). DF has been paid much attention because of its better performance for high signal-to-noise ratio (SNR) region. However, if the detection at the relay node is wrong, the errors would also be propagated to the destination node. Corresponding to DF, AF is the basic relaying method. The relaying node transmits a simply amplified signal of the received signal to the destination. It is a linear process at the relay, and is easy to be implemented due to the deduction of a detection process. However, because it also amplifies the noise, performance is reduced significantly.

From the discussion of the conventional DF and AF relay methods above, it is clearly found that DF performs better than AF in high SNR region while it is opposite for low SNR region. Consequently, CPSS-based forwarding (CPSS-F) is proposed in this paper, which achieves the advantages of both DF and AF with no need of switches between these two traditional relaying methods.

A. CPSS-based Forwarding

This section introduces the proposed CPSS-F relaying scheme. The key idea is given in this section. Different with AF and DF relaying, the CPSS-F relaying computes and transmits a soft information based on social information.

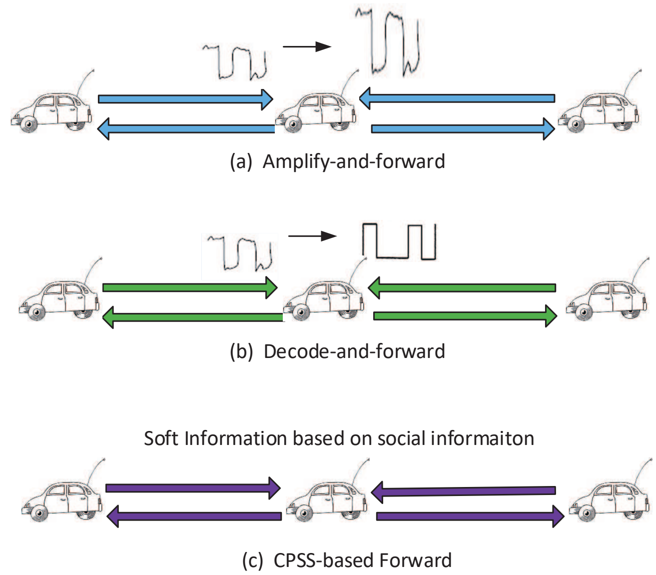

Fig. 4. The proposed CPSS-based forwarding method

Assuming that all transmitted symbols have equal priori probabilities, the optimal MMSE estimate of $\mathbf{R}$ at the relaying node [33] can be given as

$$\begin{aligned}\hat{\mathbf{R}} =& E(\mathbf{H}_1\mathbf{s}_1 + \mathbf{G}_1\mathbf{s}_2|\mathbf{R}) \\ =& \sum_{\mathcal{C}} (\mathbf{H}_1\mathbf{s}_1 + \mathbf{G}_1\mathbf{s}_2)\, P(\mathbf{H}_1\mathbf{s}_1 + \mathbf{G}_1\mathbf{s}_2|\mathbf{R}) \\ =& \frac{\sum_{\mathcal{C}} (\mathbf{H}_1\mathbf{s}_1 + \mathbf{G}_1\mathbf{s}_2)\, f(\mathbf{R}|\mathbf{s}_1, \mathbf{s}_2, \mathbf{H}_1, \mathbf{G}_1)}{\sum_{\mathcal{C}} f(\mathbf{R}|\mathbf{s}_1, \mathbf{s}_2, \mathbf{H}_1, \mathbf{G}_1)},\end{aligned} \tag{6}$$

where $\mathcal{C}$ is the set of satisfying $\mathbf{s}_1 \in \mathcal{Q}^{N_{S1}}$ and $\mathbf{s}_2 \in \mathcal{Q}^{N_{S2}}$. The probability distribution function (PDF) of $\mathbf{R}$ conditionally on $\mathbf{s}_1$, $\mathbf{s}_2$, $\mathbf{H}_1$ and $\mathbf{G}_1$ is denoted by $f(\mathbf{R}|\mathbf{s}_1, \mathbf{s}_2, \mathbf{H}_1, \mathbf{G}_1)$. Because of the i.i.d Gaussian noise, $f(\mathbf{R}|\mathbf{s}_1, \mathbf{s}_2, \mathbf{H}_1, \mathbf{G}_1)$ can be written as

$$\begin{aligned}& f(\mathbf{R}|\mathbf{s}_1, \mathbf{s}_2, \mathbf{H}_1, \mathbf{G}_1) \\ &= \frac{1}{(\pi\sigma^2)^{N_{S1}+N_{S2}}} \exp\left(-\frac{\|\mathbf{R} - \mathbf{H}_1\mathbf{s}_1 - \mathbf{G}_1\mathbf{s}_2\|^2}{\sigma^2}\right).\end{aligned} \tag{7}$$

Therefore, Eq. (6) can be computed as

$$\hat{\mathbf{R}} = \frac{\sum_{\mathcal{C}} (\mathbf{H}_1\mathbf{s}_1 + \mathbf{G}_1\mathbf{s}_2) \exp\left(-\frac{\|\mathbf{R}-\mathbf{H}_1\mathbf{s}_1-\mathbf{G}_1\mathbf{s}_2\|^2}{\sigma^2}\right)}{\sum_{\mathcal{C}} \exp\left(-\frac{\|\mathbf{R}-\mathbf{H}_1\mathbf{s}_1-\mathbf{G}_1\mathbf{s}_2\|^2}{\sigma^2}\right)}. \tag{8}$$

To satisfy the relay power constraint as with the conventional relaying methods, the coefficient is derived by $\beta = \sqrt{\frac{P_R}{E(\|\hat{\mathbf{R}}\|^2)}} = \sqrt{\frac{P_R}{\int_{-\infty}^{\infty} \|\hat{\mathbf{R}}\|^2 f(\mathbf{R}) d\mathbf{R}}}$. According to the total probability law, the probability density function (PDF) of the received signal is computed by

$$\begin{aligned} f(\mathbf{R}) &= \sum_{\mathcal{C}} f(\mathbf{R}|\mathbf{s})P(\mathbf{s}) \\ &= \sum_{\mathcal{C}} \frac{1}{(\pi\sigma^2|\mathcal{Q}|)^{N_{S1}+N_{S2}}} \exp\left(-\frac{\|\mathbf{R} - \mathbf{H}\mathbf{s}\|^2}{\sigma^2}\right),\end{aligned} \tag{9}$$

$$\hat{\mathbf{R}} = \frac{\sum_{\mathcal{C}} (\mathbf{H}_1\mathbf{s}_1 + \mathbf{G}_1\mathbf{s}_2)\exp\left(-\frac{\|\mathbf{R}-\mathbf{H}_1\mathbf{s}_1-\mathbf{G}_1\mathbf{s}_2\|^2}{\sigma^2}\right)}{\sum_{\mathcal{C}} \exp\left(-\frac{\|\mathbf{R}-\mathbf{H}_1\mathbf{s}_1-\mathbf{G}_1\mathbf{s}_2\|^2}{\sigma^2}\right)}$$

$$= \frac{\sum_{\mathcal{C}-\mathcal{L}} (\mathbf{H}_1\mathbf{s}_1 + \mathbf{G}_1\mathbf{s}_2)\exp\left(-\frac{\|\mathbf{R}-\mathbf{H}_1\mathbf{s}_1-\mathbf{G}_1\mathbf{s}_2\|^2}{\sigma^2}\right) + \sum_{\mathcal{L}} (\mathbf{H}_1\mathbf{s}_1 + \mathbf{G}_1\mathbf{s}_2)\exp\left(-\frac{\|\mathbf{R}-\mathbf{H}_1\mathbf{s}_1-\mathbf{G}_1\mathbf{s}_2\|^2}{\sigma^2}\right)}{\sum_{\mathcal{C}} \exp\left(-\frac{\|\mathbf{R}-\mathbf{H}_1\mathbf{s}_1-\mathbf{G}_1\mathbf{s}_2\|^2}{\sigma^2}\right)}. \quad (5)$$

where $\mathbf{H} = [\mathbf{H}_1\ \mathbf{G}_1]$ and $\mathbf{s} = [\mathbf{s}_1\ \mathbf{s}_2]^T$. Thus, $\beta\hat{\mathbf{s}}$ is transmitted to the opposite node. The relaying function is thus derive as

$$\mathcal{F}(\mathbf{R}) = \sqrt{\frac{P_R}{\int_{-\infty}^{\infty} \|\hat{\mathbf{R}}\|^2 f(\mathbf{R}) d\mathbf{R}}} \times \hat{\mathbf{R}}. \quad (10)$$

With the definition of $\mathcal{L}$, the symbol list within the SNR adaptive hypersphere with a radius $\frac{\rho}{\rho+\alpha}d^2$ [34] (ρ denotes the channel SNR), we can then write (8) as Eq. (5).

The second term in (5) can be computed using list sphere decoder while the first term in (5) can be approximated by an integral

$$\int (\mathbf{H}_1\mathbf{s}_1 + \mathbf{G}_1\mathbf{s}_2)\exp\left(-\frac{\|\mathbf{R}-\mathbf{H}_1\mathbf{s}_1-\mathbf{G}_1\mathbf{s}_2\|^2}{\sigma^2}\right) ds, \quad (11)$$

where the integration is over $(-\infty, \infty)$, but the elements in the list $\mathcal{L}$ needs to be removed. For instance, for one dimension scenario, if q is in $\mathcal{L}$, the integral will be

$$\int_{-\infty}^{q-\delta} s\exp\left(-\frac{|r-Hs|^2}{\sigma^2}\right) ds + \int_{q+\delta}^{\infty} s\exp\left(-\frac{|r-Hs|^2}{\sigma^2}\right) ds. \quad (12)$$

where δ is a very small value. However, for high dimension systems, it is difficult to directly compute (12). Therefore, our idea to approximate (8) is as follows.

If $\mathcal{L}$ is empty, (5) could be approximated to be

$$\begin{aligned} \hat{\mathbf{R}} &= \left(\mathbf{H}^H\mathbf{H} + \frac{\sigma^2}{\sigma_s^2}\mathbf{I}\right)^{-1} \mathbf{H}^H\mathbf{R} \\ &= \hat{\mathbf{R}}_{LMMSE}, \end{aligned} \quad (13)$$

where σ_s^2 represents the average power for the transmitted signal. Eq. (13) is derived because of the fact that the linear MMSE and the MMSE estimation are equivalent for Gaussian inputs.

Assuming that $\hat{\mathbf{R}}_{ML}$ denotes the maximum likelihood (ML) solution within $\mathcal{L}$, $\hat{\mathbf{R}}_{ML} = \arg\min_{\mathbf{R}\in\mathcal{L}} \|\mathbf{R}-\mathbf{Hs}\|^2$, we define the function as

$$\hat{\mathbf{R}} = (1-\kappa)\hat{\mathbf{R}}_{LMMSE} + \kappa\hat{\mathbf{R}}_{ML}, \quad (14)$$

which is the definition of the proposed CPSS-F algorithm. In Eq. (14), κ plays an important role in this algorithm.

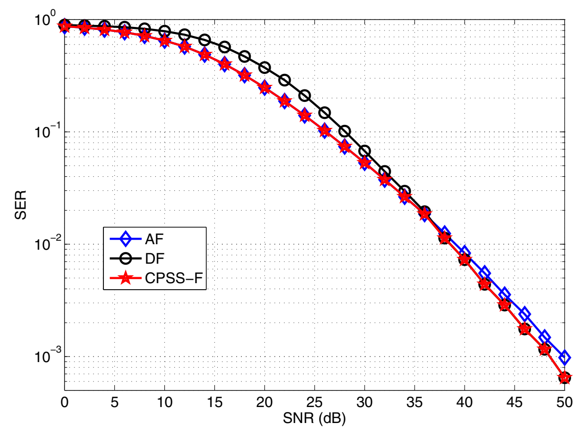

Fig. 5. SER performance comparison of relay functions at different SNRs.

In order to derive the optimal κ is to minimize the MSE of $\hat{\mathbf{R}}$, which could be shown as

$$\begin{aligned} \kappa_{opt} &= \arg\min_{\kappa\in(0,1)} \mathbb{E}\{\|\hat{\mathbf{R}} - \mathbf{Hs}\|^2\} \\ &= \arg\min_{\kappa\in(0,1)} \mathbb{E}\{\|\kappa\left(\hat{\mathbf{R}}_{LMMSE} - \mathbf{Hs}\right)\|^2\} \\ &\quad + \mathbb{E}\{\|(1-\kappa)(\hat{\mathbf{R}}_{ML} - \mathbf{Hs})\|^2\}. \end{aligned} \quad (15)$$

This parameter would be derived based on social information for different transmission scenarios from historic data.

V. Experiment Results

An example of the CPSS-F relay method is given in this section by comparing with the traditional AF and DF for cooperative vehicular networks, measured by symbol error rate (SER). It is assumed that the transmit power is equal to that at the cooperative relaying vehicle node. At the destination node, the optimal performance is achieved by using sphere detection with very low computational complexity.

As shown in Fig. 5, the performance comparison of different relaying schemes for a 16-QAM cooperative vehicular network with one relay path. As demonstrated in Section IV, the proposed CPSS-F outperforms the general AF and DF relaying for the whole SNR region. In low SNR region, the proposed CPSS-F performs similar to AF, while it achieves a similar SER performance to DF for high SNR region. Further, it does not need switches between AF and DF, and is easy to be implemented. Therefore, as aforementioned, the proposed CPSS-F achieves the optimal SER performance compared to the conventional AF and DF. Furthermore, it is worthy to mention that the CPSS-F could be extended for different types of cooperative vehicular networks with different vehicular channels and/or multi-antenna networks.

VI. Conclusions

A CPSS-based forwarding scheme based on soft estimated information was proposed and analyzed for cooperative full-duplex vehicular networks in this paper. Different with the conventional AF and DF, the proposed CPSS-F relay forwards a soft estimate of the received signal from the transmitted vehicle node (vehicle/infrastructure) to the received node (vehicle/infrastructure). Thus, the relay node achieves better trade-off between performance and complexity than AF and DF. In addition, experimental results further confirmed the advantages of the proposed CPSS-F strategy. The CPSS-F relaying would be one potential forwarding method for cooperative full-duplex vehicular networks because of its aforementioned advantages.

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