Broad-Range Null-Steering Reception in Multi-RSU Cooperative V2I-MIMO Transmission

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***Abstract*—This paper proposes a post-coding weight for vehicles under high mobility in vehicle-to-infrastructure (V2I) cooperative multiple roadside units (RSUs) transmission system. In connected autonomous vehicles (CAVs), sharing high-resolution sensor data between RSUs and vehicles is vital for safety, requiring high transmission capacity to handle large amount of data volumes. This study focuses on cooperative multi-stream transmission from multiple RSUs with low spatial correlation to further enhance the per-vehicle transmission capacity. In V2I communication, the received signal interference from multiple RSUs is challenging owing to the vehicle mobility. This paper proposes broad-range null-steering (BRNS) postcoding scheme that ensures stable multi-stream spatial multiplexing reception for vehicles under high mobility. Computer simulation demonstrates that stable communication can be achieved by employing BRNS at the receiver side.**

I. Introduction

In connected autonomous vehicles (CAVs), high-resolution sensor data must be shared in real time between vehicles and roadside units (RSUs), which enables highly accurate self-localization and contributes to safe driving [1]. To realize this goal, the use of millimeter wave (mmWave) bands that support large-capacity transmission is essential [2,3]. However, in mmWave environments, line-of-sight (LoS) propagation usually dominates, making multiple-input multiple-output (MIMO) spatial multiplexing difficult [4]. To address this limitation, coordinated beamforming and multi-stream transmission utilizing multiple RSUs with low spatial correlation are expected to be effective [5,6]. Nevertheless, in high-mobility environments, the nulls directed to different streams at the receiver side becomes outdated, leading to a degradation of spatial multiplexing performance.

To suppress the interference of received signals in the vehicle's mobility environment, broad-range null-steering (BRNS) steers additional nulls based on the angles of undesired vehicles and improves the suppression performance in downlink multi-user MIMO (MU-MIMO) system [7]. In [8], BRNS is combined with beam tracking based on QR decomposition (QRD)-based precoding weight [9], and its interference suppression performance is improved. This paper extends BRNS concept to the receiver side to further enhance transmission capacity per vehicle via cooperative transmission from multiple RSUs.

The rest of this paper is organized as follows. Section II briefly describes the system model. Sections III and IV present the theory of the proposed scheme and computer simulation results. Finally, this paper is concluded in Sect. V.

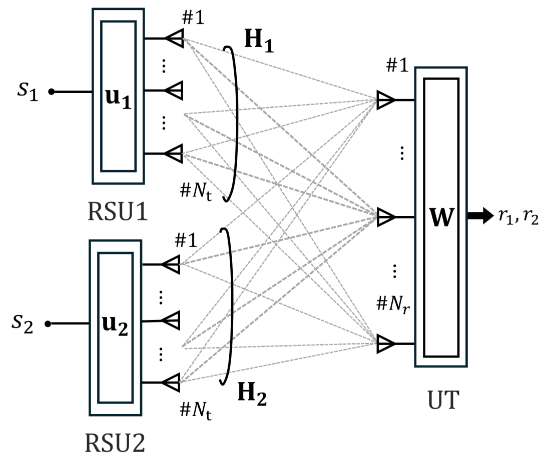

Fig. 1: System model.

Notations: Throughout the paper, matrices and vectors are written by boldfaced capital letters and lowercase letters. $(.)^T$ and $(.)^H$ indicate transpose and conjugate transpose, respectively.

II. System Model

Consider a scenario where two RSUs, each equipped with N_t antennas, transmit different two data streams $s_k\,(k = 1, 2)$ to a single vehicle as user terminal (UT) equipped with N_r antennas in the downlink, as shown in Fig. 1. Let $\mathbf{H}_k \in \mathbb{C}^{N_\mathrm{r}\times N_\mathrm{t}}$ represent the channel matrix between the k-th RSU and the vehicle, and $\mathbf{u}_k \in \mathbb{C}^{N_\mathrm{t}\times 1}$ denote the transmit precoding weight at the k-th RSU. The vehicle generates the post-coding weight $\mathbf{w}_k \in \mathbb{C}^{1\times N_\mathrm{r}}$ that perform null-steering to suppress interference from the other RSU while enhancing the desired signal in the intended direction as

$$\mathbf{w}_k\mathbf{H}_i\mathbf{u}_i \neq 0, \text{ for } i = k, \tag{1}$$
$$\mathbf{w}_k\mathbf{H}_i\mathbf{u}_i = 0, \text{ for } i \neq k, \tag{2}$$

This enables the spatial multiplexing reception of two simultaneous streams. Let the received signal r_k at the vehicle is expressed as

$$r_k = \mathbf{w}_k(\mathbf{H}_k\mathbf{u}_k s_k + \mathbf{H}_i\mathbf{u}_i s_i + \mathbf{z}_k), \text{ for } i \neq k, \tag{3}$$

where $\mathbf{z}_k \in \mathbb{C}^{N_r \times 1}$ is the additive white Gaussian noise (AWGN) vector with variance σ^2. The signal-to-interference-plus-noise power ratio (SINR) for the k-th stream at UT is then calculated as

$$\mathrm{SINR}_k = \frac{|\mathbf{w}_k \mathbf{H}_k \mathbf{u}_k|^2}{|\mathbf{w}_k \mathbf{H}_i \mathbf{u}_i|^2 + \sigma^2}. \quad (4)$$

However, in the vehicle's high mobility environments, the nulling directions to RSUs may deviate from the original direction, resulting in interference leakage and degradation of spatial multiplexing capability.

III. Proposal: BRNS-based Multi-Stream Reception

Concept of BRNS is to perform additional null-steering based on the angles of undesired UTs to improve the interference suppression performance. Section III-A shows the comprehensive description of BRNS and the post-coding weight design of QRD-based BRNS is presented in section III-B.

A. Broad-Range Null-Steering (BRNS)

Broad-range null-steering (BRNS) creates additional nulls based on the knowledge of angles of departure (AoD) or angles of arrival (AoA) to undesired targets. Assuming a uniform planar array (UPA) with size of $M \times N$ ($= N_r$), the array response coefficient of the (m, n)-th antenna element to the target, $h_{m,n}$ is expressed as

$$h_{m,n} = \exp\left(\mathrm{j}\frac{2\pi l}{\lambda}\left[(m-1)\cos\theta\sin\phi + (n-1)\cos\phi\right]\right), \quad \forall m \in \{1, \ldots, M\}, \ \forall n \in \{1, \ldots, N\}, \quad (5)$$

where l and λ denote the inter-element spacing of the antenna and the wavelength. ϕ and θ indicate the azimuth and elevation directions of the target. Array response vector can then be represented as

$$\mathbf{h}(\phi, \theta) = \left[\ h_{1,1} \ \cdots \ h_{M,1} \ \ h_{1,2} \ \cdots \ h_{m,n} \ \cdots \ h_{M,N}\ \right]. \quad (6)$$

The post-coding weight is designed to simultaneously nullify both the latest interference direction $\mathbf{h}(\phi, \theta)$ and the directionally offset channel $\mathbf{h}(\phi + \alpha_q, \theta + \beta_q)$ [8].

B. Receiver-Side BRNS Postcoding Design

The originally proposed BRNS assumed downlink transmission, while in this paper the weights are designed at the UT side as postcoding. Precisely, null-steering should be performed to the effective channel space that is the combination of channel and RSU beamforming weights $\mathbf{H}_k \mathbf{u}_k \in \mathbb{C}^{N_r \times 1}$. In a LoS-dominant environment, this can be achieved based solely on the null-steering to the direction of interfering source.

First, the matrix aggregating the Q interference vectors for the postcoding weight vector design to receive the k-th signal stream, $\mathbf{H}_k^{\mathrm{int}} \in \mathbb{C}^{N_r \times Q}$, can be defined as

$$\mathbf{H}_k^{\mathrm{int}} \triangleq [\mathbf{h}(\phi_i, \theta_i), \mathbf{h}(\phi_i{+}\alpha_1, \theta_i{+}\beta_1), \cdots, \mathbf{h}(\phi_i{+}\alpha_{Q-1}, \theta_i{+}\beta_{Q-1})]. \quad (7)$$

Here, $\mathbf{h}(\phi_i, \theta_i) \in \mathbb{C}^{N_r \times 1}$ $(i \neq k)$ is the array response vector observed from the receiver side to the i-th interference source, i.e. the i-th RSU. Based on [9], the projection matrix $\mathbf{V}_k \in \mathbb{C}^{N_t \times N_t}$ orthogonal to the interference subspace is obtained through the following procedure.

$$\mathbf{H}_k^{\mathrm{int}} = \mathbf{Q}_k \mathbf{R}_k, \quad (8)$$

$$\mathbf{V}_k = \mathbf{I}_{N_r} - \mathbf{Q}_k \mathbf{Q}_k^H, \quad (9)$$

where $\mathbf{Q}_k \in \mathbb{C}^{N_r \times Q}$ and $\mathbf{R}_k \in \mathbb{C}^{Q \times Q}$ is the unitary matrix and the upper triangular matrix, respectively.

Finally, the post-coding weight vector for k-th UT $\mathbf{w}_k$ is derived by combining the matrix $\mathbf{V}_k$ with the beamforming (maximal ratio combining) weight corresponding to the AoA of the k-th signal stream, that is the complex conjugate vector of $\mathbf{h}(\phi_k, \theta_k) \in \mathbb{C}^{N_r \times 1}$,

$$\mathbf{w}_k = \{\mathbf{V}_k \mathbf{h}_k(\phi_k, \theta_k)\}^H. \quad (10)$$

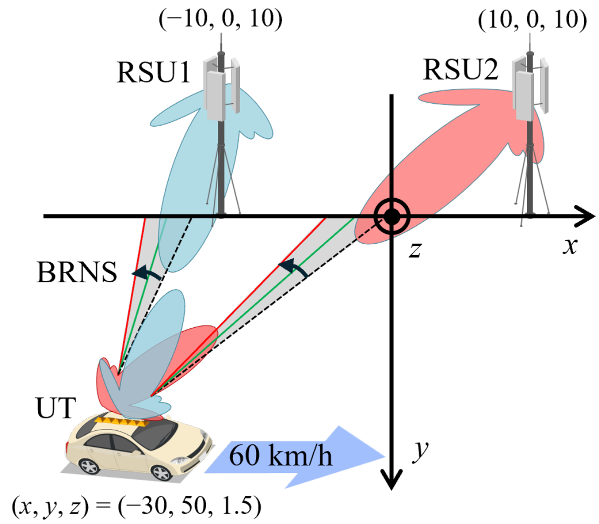

Fig. 2: Simulation envioronment.

TABLE I: Simulation Parameters.

Parameters	Values
Carrier Frequency	28 GHz
Channel Model	LoS, Free-space propagation
Tx/Rx Beamforming Update Interval	0.01 s
Rx Null-steering update interval	0.1 s
Number of RSUs	2
Number of UTs	1
UT Speed	60 km/h
Number of Antennas (RSU / UT)	100 (10x10) / 10 (10x1)
Antenna Height (RSU / UT)	10 / 1.5 m
Antenna Gain (RSU / UT)	8 / 1 dBi
Transmission Power / Feeder Loss	30 dBm / 3 dB
Receiver Noise Power	-88 dBm

IV. Computer Simulation

The simulation was conducted in a straight road environment, as shown in Fig. 2. There are two RSUs and one UT having linear array antenna. We assume that AoAs for the array response vector design in (6) are ideally estimated without noise-induced estimation errors. The following two schemes are compared in the system level simulation:

1) QRD : QRD-based orthogonalization without BRNS [9]
2) BRNS: QRD-based orthogonalization with BRNS (Proposal)

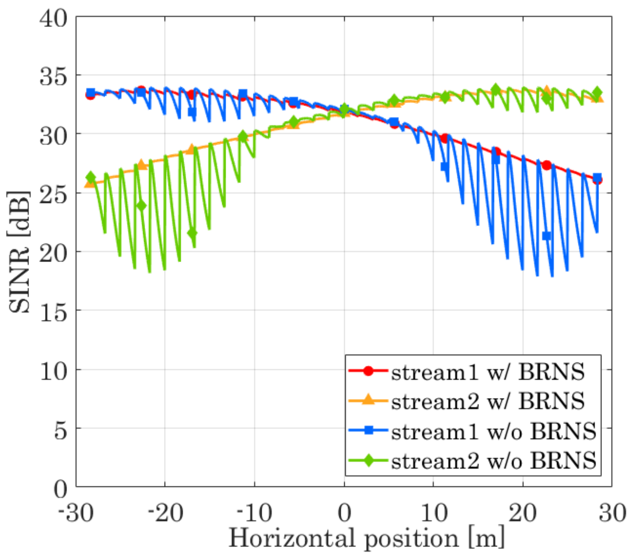

Fig. 3: SINR transition.

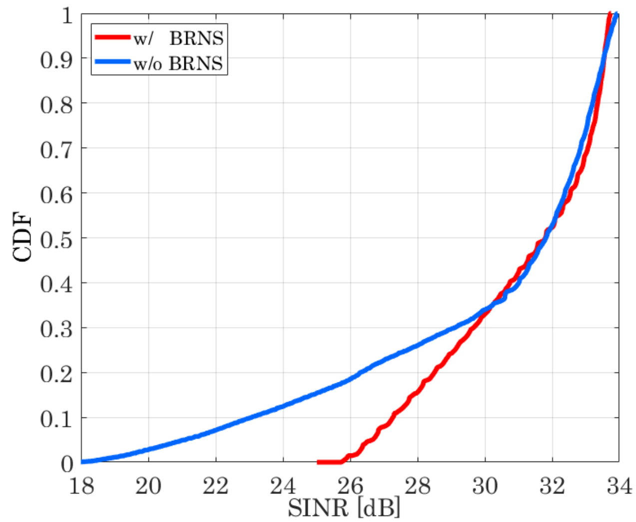

Fig. 4: Cumulative distribution function of SINR.

In the proposed BRNS, additional null-steering was implemented at horizontal direction as $(\alpha_1, \alpha_2) = (1^\circ, 2^\circ)$ degrees relative to the direction of the UT. Both the RSU and the UT are assumed to update their beam directions every 10 ms [3], while the null-steering at the UT is updated every 100 ms. Detailed simulation parameters are described in Table I.

Fig. 3 shows the SINR transition of each stream for the proposed scheme and the conventional QRD based post-coding. SINR of the conventional scheme without BRNS rapidly decreases due to the leakage of inter-stream interference whereas the proposed scheme exhibits more stable SINR transition. Fig. 4 shows the cumulative distribution functions (CDF) of SINR, confirming that the overall behavior of the proposed scheme remains stable better than the conventional one.

V. Conclusion

This paper proposed a receiver-side BRNS to stably receive multiple data stream provided by cooperated multiple RSUs. Computer simulation demonstrated its effectiveness in high mobility environment. Our future work is to extend the results to a more advanced setting where each RSU supports multi-user MIMO for multiple UTs, aiming to establish cooperative joint multi-point transmission and reception that ensures stable system capacity enhancement.

Acknowledgments

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