The effect of network delays in Vehicle-to-Vehicle (V2V) communication on the performance of the distributed optimization-based control strategy

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Mechatronics and Embedded Control Systems

Problem

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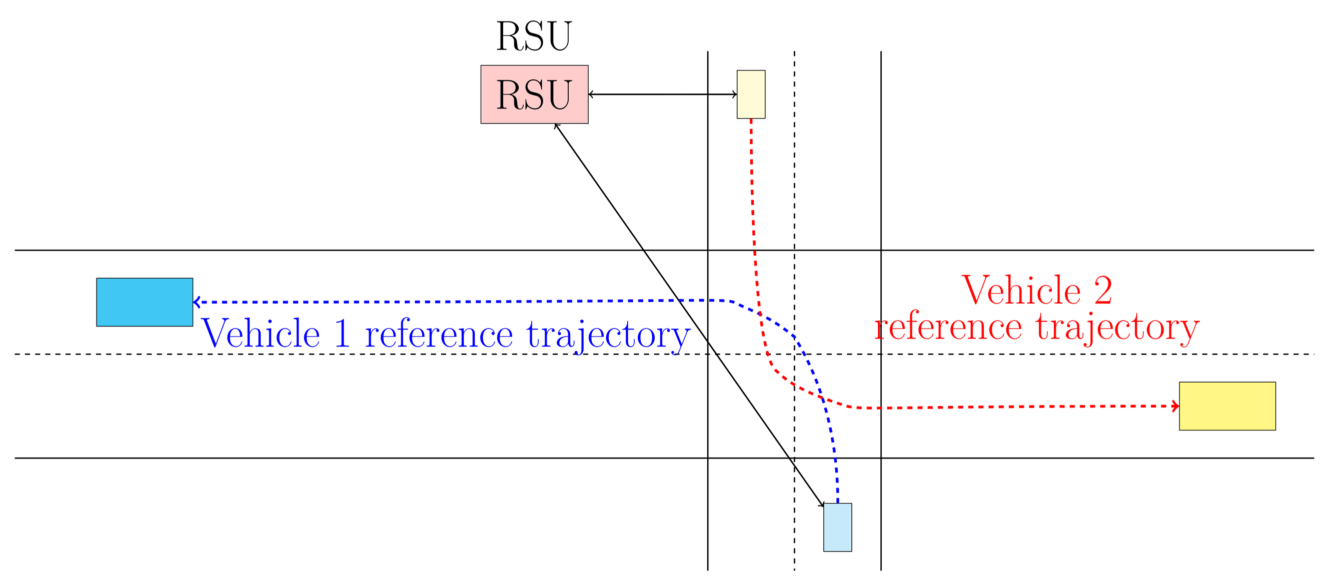

Figure 1. Traffic Intersection Scenario

The decision-making of Vehicle 1 requires the trajectory of Vehicle 2 to avoid collision. However, Vehicle 2 will continue to navigate during the time interval between Vehicle 2 sending trajectory to the RSU (V2I) and Vehicle 1 receiving it from the RSU (I2V). Due to network delays, Vehicle 1 will receive the previous trajectory of Vehicle 2 that does not contain its current information (such as current position, velocity, and orientation) (see Figure 2), which increases the risk of collision. Besides, if V2V communication encounters packet drop or unstable connection, the decision-making of Vehicle 1 at each time step will be disrupted until the required trajectory of Vehicle 2 is received. If it is received out of the time step, or in the time step but the left time to compute the next decision-making is not adequate, Vehicle 1 has no better choice but to keep using the computation result of the last decision-making until the computing of the next decision-making is finished. Therefore, the trajectory of Vehicle 1 will be affected greatly over time. Moreover, the decision-making of Vehicle 2 also requires the trajectory of Vehicle 1, and the next decision-making of UGVs is related to the last decision-making. Thus, the trajectories of Vehicle 1 and Vehicle 2 will both be affected greatly over time compared with the situation without network delays, which increases the risk of collision and navigation failure. Two connected UGVs may crash with each other, deviate from planned reference trajectories, and could not reach goal regions.

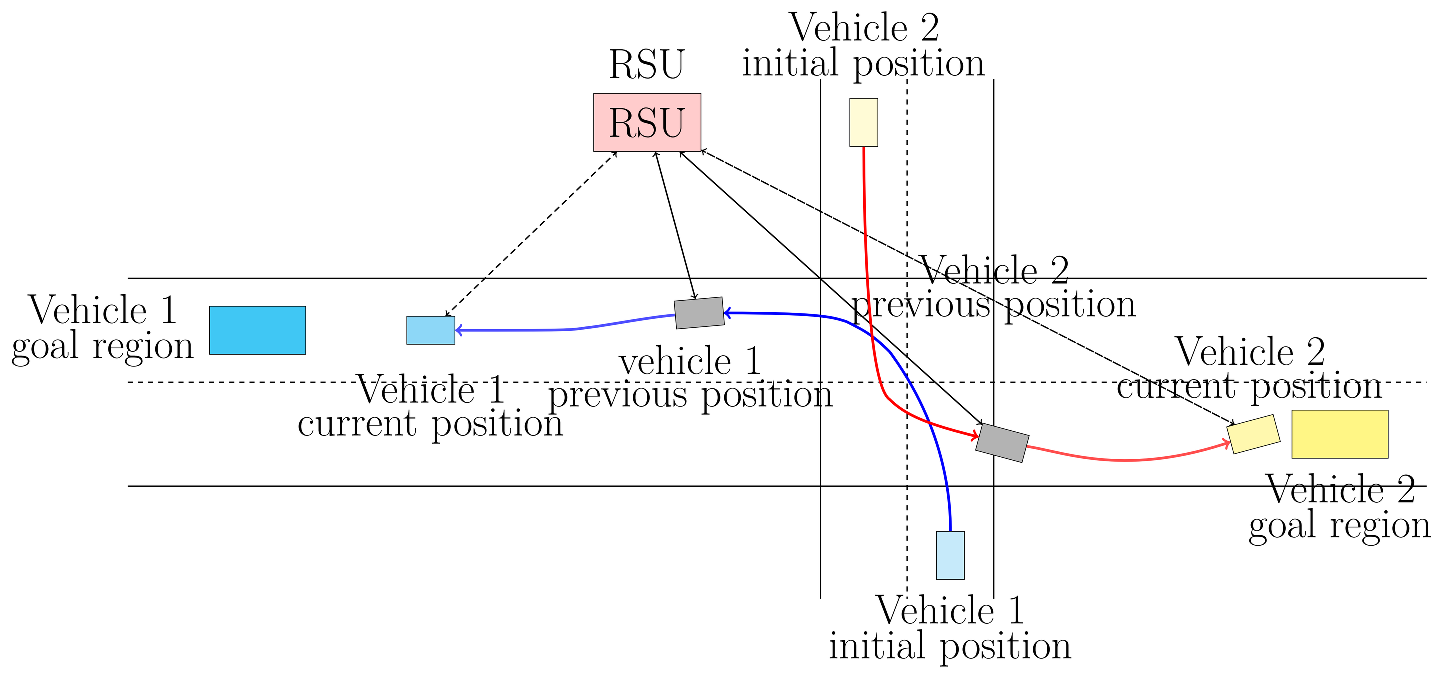

Figure 2. The effect of network delays

The networked system

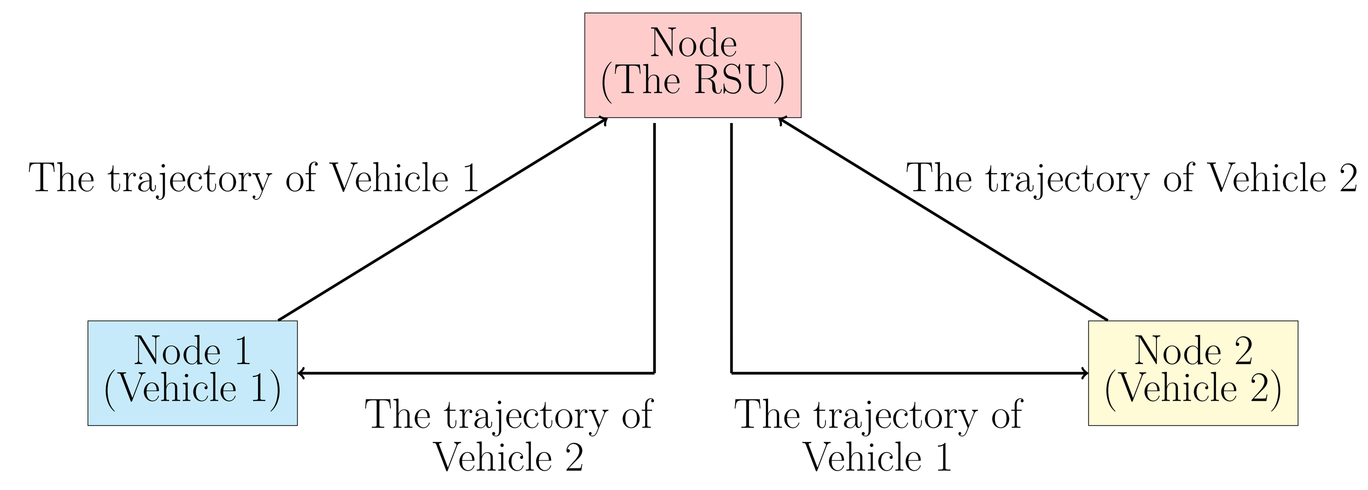

Figure 3. The networked system: a traffic intersection scenario with an RSU

Distributed Model Predictive Control

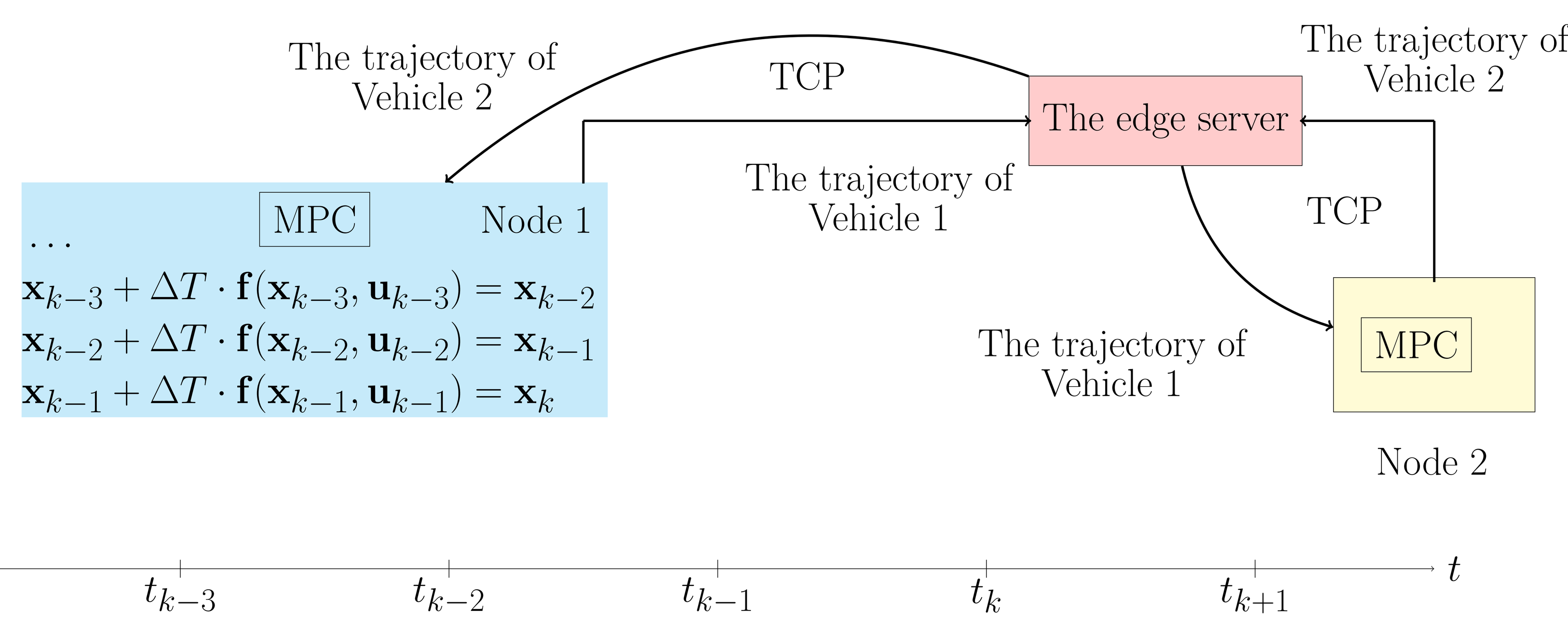

Figure 4. Nodes with discrete-time state transition and TCP communication

Optimal Control Problem

$$
\begin{aligned}
\underset{\mathcal{X}_N, \mathcal{U}_{N-1}}{\text{minimize}} \quad & \sum_{k=0}^{N-1} l((\mathbf{x}(k) - \mathbf{x}_{ref}(k)), (\mathbf{u}(k) - \mathbf{u}_{ref}(k))) + V_f(\mathbf{x}(N) - \mathbf{x}_{ref}(N)) \\
\text{subject to} \quad & \mathbf{x}(0) = \mathbf{x}_0 \\
& \mathbf{x}(k+1) = \mathbf{x}(k) + \Delta T \cdot \mathbf{f}(\mathbf{x}(k), \mathbf{u}(k)) \\
& g(\mathbf{x}(k), \mathbf{u}(k)) \leq 0 \\
& D(S_x(k), S_{x,\text{obstacle}}(k), S_y(k), S_{y,\text{obstacle}}(k)) \geq d_{\text{safety}} \\
& \mathbf{x}(N) \in \mathbb{X}_f
\end{aligned} \tag{1}
$$

where $\mathcal{X}_N$ and $\mathcal{U}_{N-1}$ are the optimization variables. $\mathcal{X}_N$ denotes a finite sequence of the local state vector, namely $\mathcal{X}_N := \{\mathbf{x}(0), \mathbf{x}(1), \mathbf{x}(2), \ldots, \mathbf{x}(N-1), \mathbf{x}(N)\}$ in which N is the prediction horizon, $\mathcal{U}_{N-1}$ denotes a finite sequence of the local control input vector, namely $\mathcal{U}_{N-1} := \{\mathbf{u}(0), \mathbf{u}(1), \mathbf{u}(2), \ldots, \mathbf{u}(N-1)\}$.

Stochastic Model Predictive Control with Chance Constraints

However, network delays in V2V communication will postpone the trajectory exchange, which causes great impacts on the formulation of the trajectory of Vehicle 2 as the inequality constraint. From the perspective of Node 1, the received trajectory of Vehicle 2 from Node 2 is the sequence of the numerical values of the local state vectors of Node 2, which can be denoted as $\mathcal{X}'_N$, namely:

$$\mathcal{X}'_N = [\mathbf{x}'(0)\ \mathbf{x}'(1)\ \mathbf{x}'(2)\ \cdots\ \mathbf{x}'(N-1)\ \mathbf{x}'(N)]$$

$$
\begin{aligned}
S_{x,\text{obstacle}}(k) &= \mathbf{x}'_1(k) \\
S_{y,\text{obstacle}}(k) &= \mathbf{x}'_2(k)
\end{aligned} \tag{2}
$$

To account for the discrepancy between the previous position and the current position, the time consumed by N2N communication (between Node 2 sending the trajectory of Vehicle 2 to the edge server and Node 1 receiving it from the edge server) will be modeled as stochastic Gaussian disturbances, namely:

$$\delta t \sim \mathcal{N}(\mu, \sigma^2) \tag{3}$$

$$
\begin{aligned}
S_{x,\text{obstacle}}(k) &= \mathbf{x}'_1(k) + \delta t \cdot \mathbf{f}_1(\mathbf{x}'(k), \mathbf{u}'(k)) \\
S_{y,\text{obstacle}}(k) &= \mathbf{x}'_2(k) + \delta t \cdot \mathbf{f}_2(\mathbf{x}'(k), \mathbf{u}'(k))
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
S_{x,\text{obstacle}}(k) &= \mathbf{x}'_1(k) + \delta t \cdot (v'(k) \cos(\Psi'(k))) \\
S_{y,\text{obstacle}}(k) &= \mathbf{x}'_2(k) + \delta t \cdot (v'(k) \sin(\Psi'(k)))
\end{aligned} \tag{5}
$$

Where $v'(k)$ and $\Psi'(k)$ are the longitudinal velocity and the heading angle of Vehicle 2, which are the fourth and fifth elements of $\mathbf{x}'(k)$, namely $\mathbf{x}'_4(k)$ and $\mathbf{x}'_5(k)$. Therefore, the discrepancy between the previous position and the current position during the time interval consumed by V2V communication is compensated. In short, the position of Vehicle 2 will be regarded as the position of the dynamic obstacle and used to formulate the inequality constraints, which can be written in the form of an if-else function, namely:

$$
\begin{array}{ll}
\begin{array}{c}\text{if with} \\ \text{network delays}\end{array} & \begin{cases} S_{x,\text{obstacle}}(k) & = \mathbf{x}'_1(k) + \delta t \cdot (\mathbf{x}'_4(k) \cos(\mathbf{x}'_5(k))) \\ S_{y,\text{obstacle}}(k) & = \mathbf{x}'_2(k) + \delta t \cdot (\mathbf{x}'_4(k) \sin(\mathbf{x}'_5(k))) \end{cases} \\
\text{else} & \begin{cases} S_{x,\text{obstacle}}(k) & = \mathbf{x}'_1(k) \\ S_{y,\text{obstacle}}(k) & = \mathbf{x}'_2(k) \end{cases}
\end{array} \tag{6}
$$