Centralized Model Predictive CACC Control Robust to Burst Communication Errors

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***Abstract*—A centralized controller computes controls and transmits them to automated vehicles. In case of a communication failure, control values will be missing and vehicles might take incorrect driving decisions. Although modern controllers may resist spurious communication errors, burst errors are expected to be more challenging. This paper introduces a centralized controller robust to burst errors. We propose a model predictive controller (MPC) computing intended *future* controls and sharing them with vehicles to be stored in a buffer. Through such buffer, vehicles may still retrieve control values even under burst errors. The proposed concept is evaluated in a mixed multi vehicle braking scenario and its superiority over other approaches in terms of distance and acceleration errors compared is shown.**

I. INTRODUCTION

In mixed traffic involving vehicles with control and communication capability like Cooperative Adaptive Cruise Control (CACC) vehicles and legacy Manually Driven Vehicles (MDVs), a CACC vehicle controller will have to predict the behavior of MDVs and compute controls based on the predicted behavior. Model mismatch arises naturally when the predicted and the actual behavior of vehicles are different. Although model mismatch cannot be completely eliminated, it can be mitigated. Repeated recomputation of controls with updated state parameters in a receding horizon fashion is the basis of Model Predictive Control (MPC) capable of countering model mismatch [1].

MPC based centralized controller requires transmission of vehicles' state parameters to the centralized server (computational unit) on the uplink and computed controls back on the downlink to the vehicles (refer Fig. 1). Communication impairments like packet delays, packet losses and out-of-order delivery of packets can thus manifest themselves either on the uplink or on the downlink. Out-of-order delivery of packets can be addressed by discarding the newly received packet if the time stamp of a newly received packet is older than that of the last received packet [2]. The occurrence of out-of-order delivery of packets also indirectly signifies packet delays (and/or losses). The impact of packet delays and packet losses on different controllers has been studied in literature.

In case of uplink packet loss, predicted behavior of MDVs can be used to estimate MDVs' state parameters. Control values from last transmission on the downlink can be used to predict future states for CACC vehicles. These estimated states can be used to compute controls [3]. String stability of a decentralized control system in case of packet delay or loss has been studied previously [4]. Switching between different control strategies based on the received information has also been proposed [5]. A centralized intersection manager coping with communication errors on the uplink is introduced in [6]. To reduce uplink and downlink packet losses for an application targeting longitudinal control of CACC vehicles, [7] focuses on various ways to decrease data transmissions.

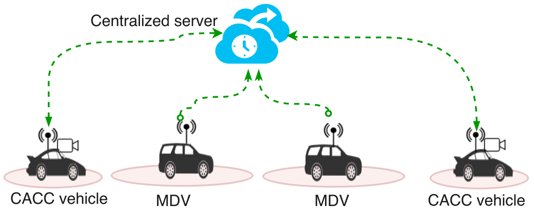

Fig. 1. A centralized controller in a mixed vehicle scenario.

Communication issues may be modeled as delayed reception, by choosing either a fixed value of delay [4], [8] or a value from a range of delays [3], [5]. Bernoulli distribution has been used to create a probabilistic packet reception scenario [6], whereas distance dependent packet delay has been implemented in [4]. It has been analytically proven that periodic transmissions face burst errors and thus lose multiple consecutive packets [9]. The use of a control buffer was recently introduced [8] to make decentralized control systems robust to communication failures. It has been evaluated in a pure CACC scenario assuming uncorrelated packet losses. The impact of MDVs as well as correlated packet losses on a centralized control system is yet to be studied.

This paper focuses on the design of a centralized control system robust to asymmetrical downlink packet losses in a mixed MDV/CACC scenario. The key contributions are as follows: 1) we propose a buffer-based centralized MPC controller resilient to burst communication errors; 2) communication errors are modeled as burst errors, a more realistic way to model real communication conditions; 3) we mitigate model mismatch generated by MDVs by periodic retransmissions of updated control values. The performance of our controller is evaluated against alternative fallback strategies when communication fails, in terms of collision avoidance and discomfort.

The rest of this paper is organized as follows: Section II introduces the centralized system and the burst error model. The buffer-based MPC controller is described in Section III. Section IV provides simulation settings and results. Concluding remarks and further challenges are provided in Section V.

II. SYSTEM DESCRIPTION

A. Centralized Control System

This work considers longitudinal control of vehicles on a single lane during a mixed vehicle braking scenario. MDV and CACC vehicles communicate using WiFi or cellular V2X technology with a centralized controller running either on a Road Side Unit (RSU) or on a remote server. On the uplink, MDV and CACC vehicles periodically transmit state parameters to the centralized controller. On the downlink, the controller transmits control values to CACC vehicles only. The received control values are locally stored in a *buffer* on each CACC vehicle. MDVs implement control behavior described in Section III-A1 whereas CACC vehicles implement controls received on the downlink. In this work, uplink communication is assumed to be perfect and only communications errors on the downlink are considered. We ignore actuation dynamics and assume the lower level controller to be perfect.

B. Burst Error Communication model

Communication in real life scenarios are subject to impairments leading to packet losses. Successful packet reception (and decoding) depends on the received signal to noise plus interference ratio (SINR), which is influenced by fading. Considering independent and identically distributed (IID) packet errors and white Gaussian fading, successive Bernoulli trials can be performed to obtain an analytical packet reception model. In practice, as illustrated by Gudmunson [10], fading is strongly correlated, leading to successive packet losses/reception. This results in a burst error channel that cannot be captured by a Bernoulli model due to non-IID losses. Instead, a two-state Markov model has been adopted by the community to capture such ‘shot-noise’ model. This approach has notably been described in [9], [11] to model the packet reception probability during periodic transmissions influenced by burst errors.

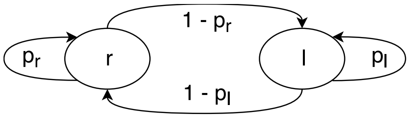

Fig. 2. Markov chain to model packet drops.

We illustrate in Fig. 2 such a discrete time stochastic first order two state Markov process. The probability of successfully receiving the next packet depends on the current link state. It is p_r, with $0 < p_r < 1$, when the link is in the reception state ($s = [1\ 0]^T$), and is $1 - p_l$, with $0 < p_l < p_r$, when the link is in the loss state ($s = [0\ 1]^T$) [9], where s is the communication state vector which is either in the reception state r or the loss state l. T represents the transition matrix between two consecutive states. We assume the transition matrix remains constant over the duration of the simulation (few tens of seconds). As long as the vehicles are within the communication range, the state vector at $(n+k)^{th}$ time slot can be given as:

$$s_{n+k} = s_n \cdot T^k \tag{1}$$

where

$$s = \begin{bmatrix} r \\ l \end{bmatrix} \quad T = \begin{bmatrix} p_r & 1-p_r \\ 1-p_l & p_l \end{bmatrix} \tag{2}$$

III. ROBUST CENTRALIZED CONTROLLER DESIGN

In this section, we first introduce model mismatch. Next we introduce a receding horizon based centralized controller and the buffer implementation to counter communication errors.

A. Model Mismatch

Model mismatch is implemented by using independent models for the actual and the assumed behavior of MDVs.

1) Actual model of MDVs: Human drivers are assumed to be controlling MDVs by implementing controls derived from IDM [12], after a certain perception response time t_{prt}. The perception response time signifies the response delay time of a human driver (refer to [13] and references therein). Note that the assumed and the actual perception response time are different.

2) Assumed model of MDVs: At each time slot n in the simulation horizon N_s the centralized controller uses a model to predict MDV braking control values $u_{i,n}$ over the entire prediction horizon N_p. Different models can be used, but we choose a simple but realistic prediction model described below.

- Before perception response time:
  the controller assumes that the driver will start braking after a certain assumed t_{prt} and increase the braking strength until it reaches a maximum. At maximum braking strength, the vehicle will continue to brake until halt.
- After perception response time:
  - *If braking magnitude is zero* - if vehicle has not started braking, controller assumes that the driver will start braking immediately and continue to increase its braking strength until the vehicle attains maximum braking strength. At maximum braking strength, the vehicle will continue to brake until halt.
  - *If braking magnitude is increasing* - the controller assumes that the vehicle will continue to increase its braking strength until the vehicle attains maximum braking strength. At maximum braking strength, the vehicle will continue to brake until halt.
  - *If braking magnitude is decreasing or constant* - the controller assumes, the vehicle will continue to brake at the previous braking magnitude until halt.

As soon as the velocity of the vehicle reaches zero each vehicle stops braking, regardless of its braking strength. Please refer to [1] for the mathematical model of the assumed MDV model, it has been omitted due to space constraints.

B. Model Predictive Control

At each time slot $n \in N_s$, the updated state parameters are used to compute controls in a receding horizon method. This recomputation of control values at each time slot helps counter uncertainties, which is the basis of a MPC controller. For each of the n_v vehicles, let the state variable x_i of a vehicle i ($i \in 1...n_v$) be defined as the position p_i, velocity v_i tuple as in (3). The relation between p_i, v_i, the actual value of control u_i and jerk Δu_i is given by (4); Δt is the time between two consecutive time slots.

$$x_i = [p_i \; v_i]^T \tag{3}$$

$$\begin{aligned} \Delta u_i(n+1) &= u_i(n+1) - u_i(n) \\ v_i(n+1) &= v_i(n) + u_i(n)\Delta t \\ p_i(n+1) &= p_i(n) + v_i(n)\Delta t + 0.5 * u_i(n)(\Delta t)^2 \end{aligned} \tag{4}$$

State dynamics of a control system in discrete form represented by (5) is used, where values for constants A and B are given by (6).

$$x_i(n+1) = Ax_i(n) + Bu_i(n) \tag{5}$$

$$A = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} \quad B = \begin{bmatrix} (\Delta t)^2/2 \\ \Delta t \end{bmatrix} \tag{6}$$

Vehicle and road constraints in terms of minimum and maximum values of position, velocity, acceleration are accounted for in (7a), and (7b).

$$\begin{bmatrix} p_i^{\min} \\ v_i^{\min} \end{bmatrix} \leq x_i(n) \leq \begin{bmatrix} p_i^{\max} \\ v_i^{\max} \end{bmatrix} \tag{7a}$$

$$u_i^{\min} \leq u_i(n) \leq u_i^{\max} \tag{7b}$$

Maximum acceleration and maximum braking is represented by $u_i^{\max}$ and $u_i^{\min}$ respectively. To ensure a smooth braking, jerk is bounded between maximum and minimum jerk values.

$$\Delta u_i^{\min} \leq \Delta u_i(n) \leq \Delta u_i^{\max} \tag{8}$$

The stream of vehicles is assumed to be moving towards the obstacle which is assumed to be at the origin. Let vehicle i be the vehicle following vehicle $i-1$. Every CACC vehicle $i \in Z$ tries to maintain positive intervehicle distance with any (MDV or CACC) vehicle in front and at the back to ensure collision avoidance (9); Z is the set of all CACC vehicles amongst n_v vehicles. Intervehicle distance is the bumper to bumper distance.

$$\begin{aligned} d_{i,i-1}(n) > 0 \quad & n_v \geq i \geq 2, i \in Z \\ d_{i+1,i}(n) > 0 \quad & n_v - 1 \geq i \geq 1, i \in Z \end{aligned} \tag{9}$$

MPC is configured such that the velocity at the end of the prediction horizon N_p is zero (10). This indirectly sets the simulation horizon N_s to infinity.

$$v_i(N_p) = 0 \tag{10}$$

We let the prediction and the control horizon N_c to be of the same length. $N_p = N_c$. The cost function J is set to penalize strong changes in acceleration to minimize discomfort.

$$\text{minimize} \quad J = \sum_{i=1}^{n_v} \sum_{\eta=1}^{N_p} \Delta u_i(\eta)^2 \tag{11}$$

$$\text{subject to}$$

$$(3),\ (4),\ (5),\ (6),\ (7a),\ (7b),\ (8),\ (9),\ (10)$$

At each $n \in N_s$, assumed control model is used predict controls for MDVs which is inturn used to predict state parameters of MDVs. These parameters corresponding to MDVs are set as constraints in (7a) and (7b). The actual control value implemented on MDV would be reflected in the updated state parameter in (3) at the next time slot. The quadratic optimization problem represented in (11) subject to assumed and actual model of MDVs is solved using QUADPROG toolbox on MATLAB.

C. *Buffer implementation*

At each successful MPC run N_p control values per CACC vehicle are generated and transmitted to the vehicle. On every packet reception, new control values replace the old buffer content and the first control value from the buffer is implemented. Affected by burst errors (or in case of computation failure) when multiple consecutive packets are lost and the buffer is not updated, consequent control values from the buffer are used. Fig. 3 illustrates one such example where the vehicle receives the first packet at the first time slot and the control values are loaded into the buffer. The first control value (shaded purple) from the buffer is implemented. Next (two) packets are lost due to burst errors, the buffer content is retained and (second and third) control values from the buffer are implemented (at second and third timeslots respectively). Communication is successful at the forth slot, the buffer is updated and the first control value is implemented.

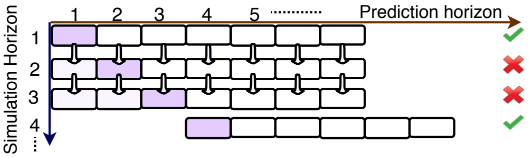

Fig. 3. Buffer implementation.

IV. Simulations and Analysis

A. *Simulation configuration*

We simulate a 4 vehicle coordinated mobility scenario on a single lane under imperfect communication conditions. The vehicle type (CACC or MDV) is randomly assigned. In all simulations, there is at least one CACC vehicle (the rest are MDVs). The simulation begins with vehicles moving at a speed of $90\,\mathrm{km/hr}$ ($25\,\mathrm{m/s}$), the first vehicle is at $120\,\mathrm{m}$ from the obstacle and rest of the vehicles initially have a time headway of $1\,\mathrm{s}$ and a fixed safety distance of $3\,\mathrm{m}$. We assume that the obstacle is stationary at the origin. Setting $p^{\min} = 0$ ensures vehicles come to a halt before colliding with the obstacle. Overtaking, lane change and going in reverse ($v^{\min} = 0$) is forbidden. $\Delta u^{\min}$ and $\Delta u^{\max}$ values are capped to -2.5 and $2.5\,\mathrm{m/s^3}$ respectively. $u^{\min}$ and $u^{\max}$ values are set to -5.88 and $2\,\mathrm{m/s^2}$. $N_p = N_c = 100$ time slots. Communication and control computation frequency are both set to 10 Hz. The parameters values used with IDM: v_0, s_0, T, a, δ, b are $25\,\mathrm{m/s}$, $3\,\mathrm{m}$, $1\,\mathrm{s}$, $1\,\mathrm{m/s^2}$, 4 and $-2\,\mathrm{m/s^2}$

respectively (parameters follow standard notation as in [12]). Vehicles have uniform length of $4\,\mathrm{m}$.

The performance of the proposed buffer based fallback strategy is evaluated in the absence and in the presence of communication errors and is benchmarked against two other fall back strategies.

1) No communication error: Simulation parameters introduced above remain the same with communications assumed to be **perfect**. This scenario represents an ideal simulation, only the first value of the control needs to be be sent per time slot (one control value of 8 Bytes) and there is no need of a buffer. This means an additional 0.64 Kbps per CACC vehicle.[1]

2) In presence of communication errors: On the downlink, when a transmitted packet is not received in the same time slot, it is assumed to be lost (no communication delay). Asymmetric communication loss is considered, meaning, packet reception for the same time slot could have been successful for some vehicles whereas a failure for others. Downlink communication loss directly impacting CACC vehicles (only) is considered.

Communication impairments have been implemented as introduced in Section II-B. Without loss of generality, two sets of values which correspond to poor communication (p_r = 0.8, p_l = 0.75) and good communication conditions (p_r = 0.998, p_l = 0.30) are used. More realistic values for these parameters can be obtained from the communication channel in real life scenarios, this is left for future work. Under non ideal circumstances when new control inputs are not received on the downlink, the vehicle switches to one of the three fallback strategies (previous, ACC or buffer):

1) the vehicle retains its **previous** applied acceleration (no buffer). i.e.: $u_i(n) = u_i(n-1)$.
2) the vehicle switches back to **ACC** mode (no buffer). i.e.: the acceleration value obtained from ACC based on IDM [12] is applied.
3) the vehicle fetches acceleration value from the **buffer** as explained in Section III-C.

During the switch to and from the fall back strategy, (8) is implemented as a filter to ensure jerks remain within limits. The first two strategies do not require a buffer, whereas the last strategy can be applied only if a buffer is present.

100 simulations are carried out for two different communication channels and each fallback strategy is evaluated using two metrics: (i) *discomfort* (2 norm of change in acceleration per time slot of the CACC vehicles)[2] (ii) *collision avoidance (CA)* during braking. Simulation results have been summarized in Table I and II. The average *Packet Loss Ratio (PLR)* over all simulation runs are also mentioned.

B. Simulation Results

Out of these 100 simulations, we select and analyze a particular scenario where vehicles are arranged as [CACC; MDV; CACC; MDV]. The first CACC vehicle is the leading vehicle. The simulation terminates without collisions. Refer to the Fig 4, which shows the acceleration plot of the third vehicle (CACC) under different fallback strategies (Previous, ACC and Buffer) in presence of burst communication errors (p_r = 0.8 and p_l = 0.75). We can observe that the ACC fallback mode under communication error has a lot of jumps and is not comfortable compared to the (Perfect) plot without communication error. The use of a buffer based strategy is superior to other fall back strategies because the average value of discomfort is better than that of the other strategies (refer to Table I). Corresponding plot of the *distance to front vehicle* is plotted in Fig. 5. The plot of the buffer and perfect cases are similar, illustrating no safety drawback from the use of the proposed buffer.

TABLE I
CACC SUBJECT TO BURST ERRORS WITH p_r = 0.8 AND p_l = 0.75

	No communication error (Perfect)	Presence of communication errors		
		Previous	ACC	Buffer
Discomfort	2.0320	2.4763	6.0457	2.0791
CA (%)	77	77	72	77
PLR (%)	–	42.6518	42.2012	42.0442

TABLE II
CACC SUBJECT TO BURST ERRORS WITH p_r = 0.998 AND p_l = 0.30

	No communication error (Perfect)	Presence of communication errors		
		Previous	ACC	Buffer
Discomfort	2.0320	2.0335	2.1206	2.0328
CA (%)	77	77	77	77
PLR (%)	–	1.9423	1.9418	1.9423

Different fallback strategies might take different time to terminate the simulation. This can also be visualized in Fig. 4, 5 where the simulation with ACC terminates around the 200th time slot, whereas others take longer. Over different simulation duration, the value of PLR lost can be different.

The performance of these strategies evaluated over different types of communication channels shows that poor communication channel (higher PLR) results into greater discomfort in general and could even result into more number of collisions (refer to Tables I and II). Overall, we observe an approximate 21.74% increase in collisions (an increase of 5 from 23 to 28) whilst using ACC based fallback strategy compared to other strategies under poor communication conditions. To summarize buffer based MPC design has a better performance compared to other fallback options assessed in this work. No additional collisions occurred and the discomfort level was lower compared to other options which were evaluated.

C. Communication Overhead

Comfort and safety in such a centralized braking system comes at the cost of additional data overhead on the downlink. For the system described in this paper, N_p values per CACC vehicle are transmitted on the downlink at $10\,\mathrm{Hz}$. Considering a control value as a double variable (8 Bytes), data overhead

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[1] The presence of model mismatch necessitates a regular computation and transmission of updated control inputs to the vehicles; if model mismatch is absent, just one transmission with N_p values should ideally be sufficient.

[2] Computed only if the simulation ends without any collisions.

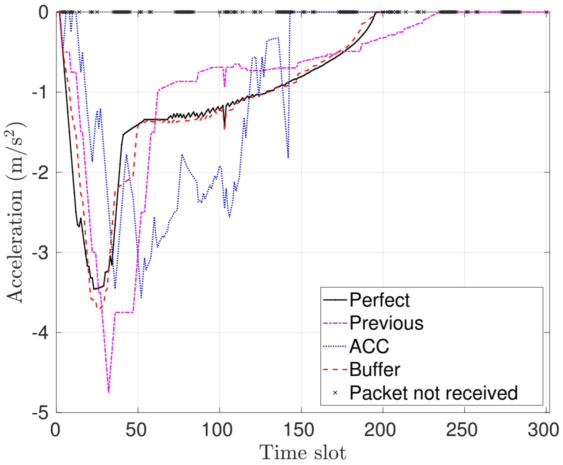

Fig. 4. Control inputs under different feedback strategies in presence of communication errors.

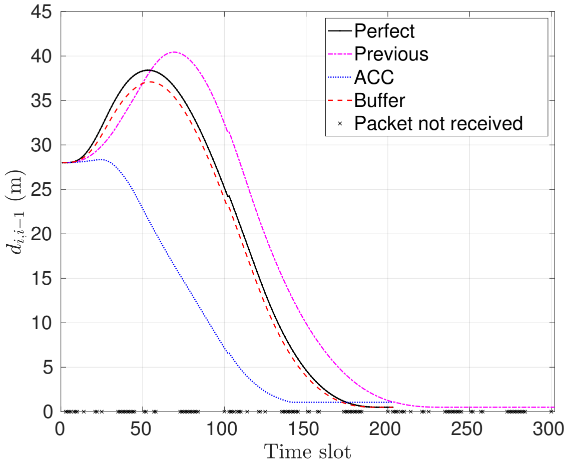

Fig. 5. Distance between ego vehicle and the vehicle in front.

is 64 Kbps per CACC vehicle. Without loss of generality, considering a target 60 % channel load (at 6 Mbps), 3.6 Mbps data rate can theoretically be allocated, allowing approximately 56 CACC vehicles to be coordinated. As reference consider the experiment accomplished in [8], where a decentralized algorithm implemented a 25 Hz communication system with a prediction horizon of 30 slots leading to 48 Kbps of 'CAM' like data per CACC vehicle in a pure CACC traffic. The load contribution of the centralized braking application depends on the prediction horizon, number of vehicles and the required communication update frequency. This additional load may lead to communication failure. Risk analysis of collisions between vehicles because of reducing either prediction horizon or communication frequency is left to future work.

V. CONCLUSIONS

A Model Predictive Control (MPC) based centralized controller robust to burst errors on downlink communication has been proposed. It involves storing future intended acceleration values in a buffer located on the vehicle. A braking scenario involving cooperative adaptive cruise control (CACC) vehicles and manually driven vehicles (MDVs) is evaluated. Under downlink communication impacted by burst errors, the proposed controller's performance with buffer is similar to the case with no communication errors and is superior to two other buffer-free fall back strategies. In future work, we will focus on evaluating buffer size requirements based on communication channel capacity to keep an acceptable data overhead. Moreover, the impact of positioning, control and communication errors together in a centralized controller will be evaluated.

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