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A New Adaptive Modulation and Coding Method for Communication-Based Train Control Systems using WLAN ⋆

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Abstract: In this paper, we propose a new Adaptive Modulation and Coding (AMC) method for Communication-Based Train Control (CBTC) systems using Wireless Local Area Network (WLAN). The goal of the proposed method is to enhance the control performance by choosing a transmission mode which decreases the average delay with respect to both Medium Access Control (MAC) contention and channel fading according to both average Signal-to-Noise Ratio (SNR) and the number of competing vehicles. The effectiveness of the proposed method is shown via computer simulations.

Keywords: AMC, CBTC, WLAN, MAC, channel fading.

1. INTRODUCTION

With a growing number of people commuting by means of urban rail transportations in various countries, the requirements for operation efficiency and safety in urban rail transit are becoming more stringent than before. Communication-Based Train Control (CBTC) system is one of the promising methods for meeting those demands. Unlike the track circuit used in traditional train control systems, CBTC is able to use the bidirectional wireless communication between wayside equipment and the moving vehicle to improve operational flexibility and transportation capacity while ensuring safety.

However, due to various factors inherent to the mobile environments, there is a communication latency of packet delivery between wayside Access Points (APs) and trains, which may cause unnecessary train braking due to communication blackout. This braking will deteriorate the control performance including the ride comfort and energy cost. Thus, recent works such as Zhu et al. (2012),Wang et al. (2015) have proposed the Multiple-Input Multiple-Output (MIMO) enabled Wireless Local Area Networks (WLANs) for CBTC systems to achieve better control performance by improving the wireless communication performance, where they consider the design of adaptive modulation and coding for CBTC systems using Carrier Sense Multiple Access/Collision Avoidance (CSMA /CA) protocol by minimizing the average delay between the moving vehicle and wayside AP. Nevertheless, the impact of channel fading and Medium Access Control (MAC) layer contention due to multiple competing vehicles have not been considered, while they would have a large impact on the communications' delays.

In this paper, we propose a new design of Adaptive Modulation and Coding (AMC) for CBTC systems with CSMA/CA protocol considering the impact of fading channels and MAC layer contention. We perform the average delay analysis which includes the impact of the number of competing terminals and channel error, and derive the average delay of each scheme in different situations. Then, by using some information about the number of competing terminals and path loss during the train operation, we can select a proper transmission mode which minimizes this average delay in each control period to improve the control performance. The effectiveness of our approach is confirmed through computer simulations.

2. CBTC SYSTEMS AND PREVIOUS WORK

In this section, we introduce the system model considered in this paper, which is basically the same as that in Zhu et al. (2012).

2.1 CBTC Architecture

Fig.1 shows five subsystems in CBTC systems including Automatic Train Supervision (ATS), Automatic Train Operation (ATO), train-ground communication, Zone Controller (ZC) and Automatic Train Protection (ATP). The task of ATS is to set the train travel time between two neighboring stations and generate the timetable for each train. ATO subsystem on the train could produce the optimal train guidance trajectory Wang et al. (2015). The

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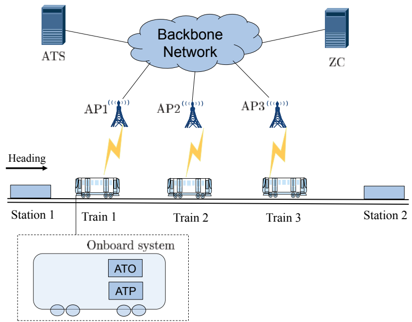

Fig. 1. Communication-based train control system

guidance trajectory is a distance versus velocity profile, which represents the optimal velocity at a specific position. Moreover, ATO can control the train velocity under this trajectory according to train travel time and other factors such as energy cost. In train-ground communication subsystem, each train needs to transmit its own location, direction, velocity and identity to the wayside AP. Then, AP transfers these information to both ZC and ATS subsystem so that ZC subsystem can send the Movement Authority (MA) which represents the allowed distance for the train to proceed. An MA of a train means the distance between the tail of this train and the obstacle in front of this train. For example, from the perspective of train 1 in Fig.1, MA is the distance between the tail of train 1 and the tail of train 2. With the constraint of MA, ATO subsystem will control the train velocity as much as possible under the guidance trajectory. The ATP subsystem is responsible for calculating the braking curve according to the updated MA, which guarantees the train safety. For the train-ground communication subsystem, WLANs have been adopted for some cases because of the commercial off-the-shelf equipments and the philosophy of open standard and interoperability Whitwam (2003).

2.2 System model

The equations of motion of the train can be written as

$$q_{k+1} = q_k + v_k T + \frac{1}{2}\frac{u_k}{M}T^2 - \frac{1}{2}\frac{w_k}{M}T^2,$$
$$v_{k+1} = v_k + \frac{u_k}{M}T - \frac{w_k}{M}T, \tag{1}$$

where q_k, v_k, u_k, w_k and T are train position, train speed, control signal, the resistance at time k and the control period, respectively. Then, according to these equations, the train state space equation can be written as

$$\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{B}u_k + \mathbf{C}w_k, \tag{2}$$

where

$$\mathbf{x}_k = \begin{pmatrix} q_k \\ v_k \end{pmatrix}, \mathbf{A} = \begin{pmatrix} 1 & T \\ 0 & 1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} \frac{1}{2M}T^2 \\ \frac{1}{M}T \end{pmatrix},$$

$$\mathbf{C} = \begin{pmatrix} -\frac{1}{2M}T^2 \\ -\frac{1}{M}T \end{pmatrix}.$$

The linear quadratic cost is taken as the control performance measure as

$$J_N = E\left[\sum_{k=0}^{N}(\mathbf{e}_k^{\mathrm{T}}\mathbf{Q}\mathbf{e}_k + Ru_k^2)\right], \tag{3}$$

where $\mathbf{e}_k = \mathbf{x}_k - \tilde{\mathbf{x}}_k$ is the tracking error, $\tilde{\mathbf{x}}_k$ is the desired train state obtained from train guidance trajectory, $\mathbf{Q}$ is a diagonal semi-definite matrix and R is a positive scalar.

In every control period T, each train sends its own location, direction, velocity and identity to ZC via a wayside AP to calculate the MA, and the MA is sent to the following train via AP. If the communication delay of sending MA is larger than T, the MA cannot be updated under this control period and packets will be discarded. Consequently, the control signal u_k is replaced by brake deceleration a (≤ 0) due to a communication interruption of T for ensuring safety. In this paper, we define such event as an outage.

2.3 Previous work

In previous work Zhu et al. (2012), CSMA/CA based MIMO CBTC system has been proposed to achieve better control performance, which focuses on minimizing the average delay. Define W_i as the contention window at the i-th backoff stage. Then, W_i for the exponential backoff strategy is given by

$$W_i = \begin{cases} 2^i W_0 & i \leq m' \\ W_{m'} & i > m', \end{cases}$$

where m' represents the backoff stage of the maximum contention window. The packet delay $T_{\mathrm{mac}}(i)$ at the i-th retransmission time is shown as

$$T_{\mathrm{mac}}(0) = T_{\mathrm{DIFS}} + \sigma(W_0 - 1)/2 + T_{\mathrm{data}}$$
$$+ T_{\mathrm{SIFS}} + T_{\mathrm{ack}},$$
$$T_{\mathrm{mac}}(i) = T_{\mathrm{mac}}(i-1) + T_{\mathrm{DIFS}} + \sigma(W_i - 1)/2 + T_{\mathrm{data}}$$
$$+ T_{\mathrm{SIFS}} + T_{\mathrm{ack}},$$

where $i \in [0, m]$, m is the maximum retransmission time, σ is the duration of an empty slot time, T_{DIFS} is Distributed Inter-frame Spacing (DIFS), T_{SIFS} is Short Inter-frame Spacing (SIFS), $T_{\mathrm{data}} = F_{\mathrm{data}}/R$ is time to transmit a data frame, F_{data} is the data payload in bits, R is the data transmission rate, $T_{\mathrm{ack}} = F_{\mathrm{ack}}/R$ is time to transmit the acknowledgement frame and F_{ack} is the acknowledgement frame in bits.

Define D_k as the average delivery delay between AP and train at time k, then D_k can be calculated by

$$D_k = (1 - p_{\mathrm{e},k})T_{\mathrm{mac}}(0) + p_{\mathrm{e},k}(1 - p_{\mathrm{e},k})T_{\mathrm{mac}}(1) + \cdots$$
$$+ p_{\mathrm{e},k}^{m-1}(1 - p_{\mathrm{e},k})T_{\mathrm{mac}}(m-1) + p_{\mathrm{e},k}^{m}T_{\mathrm{mac}}(m), \tag{4}$$

where $p_{\mathrm{e},k}$ is the Frame Error Rate (FER) at time k.

Then the optimization problem in previous work becomes

$$\min_{R_k, p_{\mathrm{e},k}} D_k.$$

Note that the data transmission rate R_k is determined by the Modulation and Coding Scheme (MCS) and FER $p_{\mathrm{e},k}$ is influenced by the selection of the MCS and channel state. As a result, the MCS which minimizes the optimization problem above is chosen according to the average Signal-to-Noise Ratio (SNR) in every control period.