Cross-Layer Handoff Design in Communication-Based Train Control (CBTC) Systems Using WLANs

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Abstract Communication-Based Train Control (CBTC) system is an automated train control system using bidirectional train-ground communications to ensure the safe operation of rail vehicles. Handoff design has significant impacts on the train control performance in CBTC systems based on multi-input and multi-output (MIMO)-enabled WLANs. Most of previous works use traditional design criteria, such as network capacity and communication latency, in handoff designs. However, these designs do not necessarily benefit the train control performance. In this paper, we take an integrated design approach to jointly optimize handoff decisions and physical layer parameters to improve the train control performance in CBTC systems. We use linear quadratic cost for the train controller as the performance measure. The handoff decision and physical layer parameters adaptation problem is formulated as a stochastic control process. Simulation result shows that the proposed approach can significantly improve the control performance in CBTC systems.

I. Introduction

Communication-based train control (CBTC) is an automated train control system for railways that ensures safe operation of rail vehicles using data communications [1]. It can improve the utilization of railway network infrastructure and enhance the level of safety and service offered to customers.

Train-ground communication is one of the key technologies in CBTC systems. For urban mass transit systems, IEEE 802.11a/b/g based WLANs has been widely adopted as train ground technology due to the available commercial-off-the-shelf equipments [2] and the philosophy of open standards and interoperability [3]. We will focus on WLAN-based CBTC systems in this paper.

Building a control system over wireless networks is a challenging task. A communication network inevitably introduces random packet delay and losses. The problem is more pronounced in CBTC systems, where the communication environment is very complex between a fast moving train and ground. While packet delay and losses mean poor quality of service (QoS) in commercial wireless network; in CBTC systems, packet delay and losses could cause train derailment, collision or event catastrophic events. Particularly, when a train moves away from the coverage of a WLAN access point (AP) and enters the coverage of another AP along the railway, a handoff procedure occurs. This handoff process may result in communication interrupt and long latency, which could severely affect train control performance, train operation efficiency, and the utilization of railway network infrastructure.

Although many works have been done to address the handoff problem, few of them consider high speed train environment. The fast movement of high speed trains causes frequent handoffs, which could severely affect CBTC performance. In addition, most of previous works are focused on handoff protocols, and consequently handoff decision policy issues (i.e., when to perform handoff) are largely ignored, which should be carefully considered in high speed train environment. More importantly, traditional design criteria, such as network capacity and communication latency, are used in existing works in handoff design. However, recent works in cross-layer design show that maximizing capacity or minimizing latency does not necessarily benefit the application layer [4], which is train control in CBTC systems. From CBTC perspective, the performance of train control is more important than that at other layers. A commonly used control performance measure is the linear quadratic cost [5], which is directly related to train control accuracy, train safety, and passengers ride quality [6].

In this paper, we study the cross-layer handoff design issues in MIMO-enabled WLANs for CBTC systems. The linear quadratic cost for the train controller in CBTC systems is considered as the performance measure in the handoff design. We formulate the handoff decision and MIMO parameters adaption problem as a Semi-Markov Decision Process (SMDP) [7]. Extensive simulation results are presented. We show that handoff design has significant impact on the train control performance in CBTC systems.

II. Communication-Based Train Control (CBTC) Systems

In this section, we first present an overview of CBTC systems. Then, we describe the proposed CBTC system based on MIMO-enabled WLANs.

A. Overview of CBTC Systems

As shown in Fig. 1, a CBTC system consists of five subsystems. They are Automatic Train Supervision (ATS) subsystem, Automatic Train Operation (ATO) subsystem, Automatic Train Protection (ATP) subsystem, Zone Controller (ZC) subsystem, and train ground communication subsystem. The ATS subsystem

This work was in part supported by Beijing Jiaotong University Technology Funding Project (NO.KWJB11082536, and NO.2011JBZ014) National Science Foundation of China (NO.61132003), Key Projects in State Key Lab. of Rail Traffic Control and Safety (NO. RCS2010ZT007, NO. RCS2010ZZ003), and by the Natural Sciences and Engineering Research Council (NSERC) of Canada and industrial and government partners, through NSERC-DIVA Strategic Research Network.

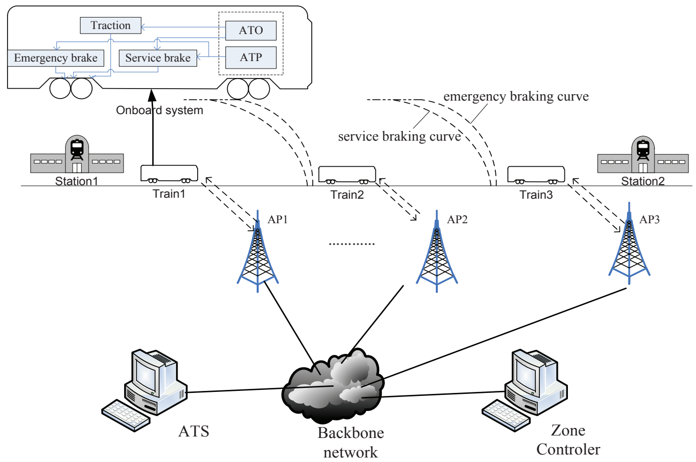

Fig. 1. A communication-based train control (CBTC) network.

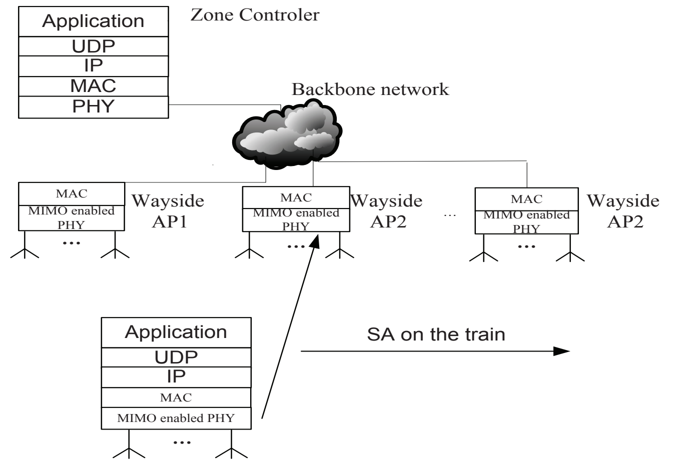

Fig. 2. System architecture and protocol stack of the proposed CBTC system based on MIMO-enabled WLAN.

makes timetables for each train, it sets the trip time between two stations. Based on the trip time given by ATS and other performance indices, such as energy savings, and passengers comfort, the ATO subsystem derives an optimized guidance trajectory. The main task of ATO subsystem is to bring the train to this derived guidance trajectory.

In CBTC systems, continuous bidirectional wireless communications between each station adapter (SA) on the train and the ground access point (AP) are adopted. In every communication period, the train and ground equipments send the corresponding information to each other after processing the received information. Communication latency and/or packet losses in wireless communications between train and ground equipments make the train travel off the guidance trajectory. Substantial energy will be lost during this process, and it will severely affect passenger comfort. More importantly, it will increase the trip time between stations, which will affect the operation of all the trains behind. In order to mitigate the impacts of wireless communications on CBTC performance, we propose a CBTC system based on MIMO-Enabled WLANs, which will be introduced in the next subsection.

B. The Proposed CBTC System Based on MIMO-Enabled WLANs

Fig. 2 describes the proposed CBTC system based on MIMO-enabled WLANs. The train control messages between train and ground, being encapsulated in User Datagram Protocol(UDP), are then transferred between trains and wayside equipments using IP and WLANs with IEEE 802.11 MAC and MIMO-enabled physical layer.

In CBTC systems, when a train travels in between successive APs, the received Signal to Noise Ratio (SNR) changes rapidly. Therefore, efficient handoff decision policy and physical layer parameters adaption policy are needed to decide at what time to trigger handoff and what physical layer parameters should be adapted, which will be studied in the following sections.

III. System Models

In this section, we first present the train control model. The communication model is described next.

A. Train Control Model

According to the train dynamics, the train state space equation can be written as

$$\begin{cases} q(k+1) = q(k) + v(k) * T + \frac{1}{2}\frac{u(k)}{M}T^2 \\ -\frac{1}{2}\frac{w_i(k)+w_r(k)+w_w(k)}{M}T^2, \\ v(k+1) = v(k) + \frac{u(k)}{M} * T - \frac{w_i(k)+w_r(k)+w_w(k)}{M}T, \end{cases} \tag{1}$$

where T is the sample rate, which depends on the communication period, $q(k)$ is the train position at time k, $v(k)$ is the train velocity, M is the train mass, $w_i(k)$ is the slope resistance, $w_i(k)$ is the curve resistance, w_w is the wind resistance, and $u(k)$ is the train control command from the train controller.

We assume the train controller is linear time invariant in discrete time and has the following state space model,

$$\begin{cases} x_c(k+1) = A_c x_c(k) + B_c y(k), \\ u(k) = C_c x_c(k), \end{cases} \tag{2}$$

where $y(k)$ is the controller input, which includes the states of the two trains.

We consider the linear quadratic cost as our performance measure in this paper. Specifically, the controller described in (2) is designed to minimize $J_{LQG} = \sum_{k\to\infty}[(z(k) - \widetilde{z}(k))^{'}Q(z(k) - \widetilde{z}(k)) + u^{'}(k)Ru(k)]$, where $z(k) = C_o x(k)$ is the observed train states, $\widetilde{z}(k)$ is the destination train states, the weight matrix Q is positive semi-definite, and R is positive definite. We can tune the system performance by choosing different Q and R.

B. Communication Model in MIMO-Enabled WLANs

In this paper, we use finite-sate Markov channel (FSMC) models in CBTC systems. In real systems, the values of the above transition probability can be obtained from the history observation of the CBTC system.

The diversity gain and spatial multiplexing gain can be realized with a MIMO system, and there is a fundamental tradeoff between them [8]. For each spatial multiplexing gain r, the best diversity gain $d^*(r)$ is the supremum of the diversity gain achieved over all schemes. With long enough block lengths, the optimal multiplexing-diversity tradeoff $d^*(r)$ is given by the piecewise-linear function connecting the points $(r, d^*(r))$ for $r = 0, 1..., min(M_A, M_S)$ [8], and $d^*(r) = (M_A - r)(M_S - r)$, where M_A and M_S are the number of transmit and receive antennas, respectively.

If the wireless link from the train SA to the wayside AP has an average SNR γ, with a multiplexing gain r, the link data rate $C(r)$ and Bit Error Probability (BER) $BER(r)$ can be approximated as [9] $C(r) = k_c r * log_2(\gamma)$, and $BER(r) = k_p * \gamma^{-d(r)}$. Where k_c and k_p are positive constants for different coding schemes, and the multiplexing gain r and diversity gain $d(r)$ satisfy the optimal tradeoff.

Given the link BER, the corresponding Frame Error Rate (FER) is derived as $FER = 1 - (1 - BER)^{L_{fr}}$, where L_{fr} is the MAC layer frame length in bits.

IV. Cross-Layer Handoff Optimization in the Proposed CBTC System

According to the train control model we described in Subsection III-A, the service brake started by ATP subsystem due to communication latency will make the train travel off the optimized guidance trajectory, which degrades the train control performance. With the aim to optimize the train control performance, the handoff decision and MIMO parameters adaptation problem in the CBTC systems is formulated as an SMDP [7]. An SMDP model consists of the following five elements: (1) decision epochs, (2) states, (3) actions, (4) rewards, and (5) transition probabilities, which will be presented in the following subsections.

A. Action and State

In our SMDP model, at each decision epoch, the SA on the train has to decide whether the connection should use the current chosen AP or connect to the next AP (we assume the SA on the train won't be in the coverage of 3 successive APs). Secondly, the multiplexing gain in physical layer should be decided. We assign every AP along the railway with a distinct number. Let N_{AP} be the AP that covers the SA, then the other one is $N_{AP}+1$. The current composite action $a(k) \in A$ is denoted by $a(k) = \{a_h(k), a_r(k)\}$, where $a_h(k)$ is the handoff action, ($a_h(k) = N_{AP} + 1$ means handoff to the next AP, $a_h(k) = M$ means stay in the old AP), $a_h(k)$ is the multiplexing gain action ($0 < a_r(k) < min(M_A, M_S)$).

The current composite state $s(k) \in S$ is given as $s(k) = \{\gamma_1(k), \gamma_2(k), \xi(k), H(k), \varepsilon(k)\}$, where $\gamma_1(k)$ and $\gamma_2(k)$ are the measured SNR from two successive APs, respectively, $\xi(k)$ is the current used AP, $H(k)$ is the handoff indicator to show if the handoff is finished, and $\varepsilon(k)$ is the velocity tracking error which is the error between the current train velocity and the destination velocity. The destination velocity is obtained based on the position of the front train and the deceleration that defines the braking curve.

Both $\gamma_1(k)$ and $\gamma_2(k) \in \{\gamma_1, \gamma_2 ... \gamma_L\}$, where L is the number of states in the channel model. $\xi(k) \in \{M, M+1\}$, because the current used AP is completely determined by the current action. The handoff indicator $H(k) \in \{0, 1, 2..., N_H\}$. When $H(k) \neq 0$, it means the SA is in handoff process. $H(k)$ increases every decision epoch in handoff process, and it reaches N_H when the handoff is finished. The velocity tracking error ε is obtained by comparing the current train velocity with the destination velocity, and the destination velocity is calculated based on the distance between the two trains.

B. Reward Function

Reward function reflects the reward that can be obtained under a certain state and action. With the objective to minimize linear quadratic cost function, we define the reward function as the reciprocal of the sum of tracking error and control magnitude. The reward function is closely related to the communication latency in the CBTC system. Therefore, we first derive the communication latency. Then, we present the rewards under different circumstances.

There are two causes of packet transmission failure in WLANs. One is the packet collision where two nodes transmit simultaneously. The other one is the channel error, where a packet is received without packet collisions and is corrupted due to low SNR. We only consider the packet transmission failure caused by channel error in this paper because, normally, there is only one SA in each AP cell in our proposed train-ground communication system. This is due to the fact that trains must keep a distance far enough between each other in order to guarantee safety.

With packet loss caused only by channel error, when a packet is transmitted n times in the MAC layer, the corresponding packet delay $T_{MAC}(n)$ in CSMA/CA systems can be calculated as in [10].

The average MAC layer packet transmission delay is dependent on the physical layer transmission data rate and the retransmission time. Given a certain SNR, a higher multiplexing gain r will give a higher capacity link which contributes to the time T_{data} needed to transmit a data frame. However, the diversity gain d will decrease with the increase of the multiplexing gain. The corresponding FER increase will lead to an increasing transmission time that, ultimately, brings in more overhead.

The handoff procedure followed by most 802.11 mobile stations [11] can be divided into three steps, namely probing (also referred to as scanning), authentication and re-association. Six packets are transmitted between the SA and AP before the handoff ends, and the average time needed to finish the handoff is approximately $6*T_{average}(r)+T_{process}$, where $T_{average}(r)$ is the communication latency and $T_{process}$ is the processing time in the AP and SA before they send new packets. The SA will continue to send probe packets periodically with the period T_{period_probe} until it gets into the authentication phase. If any one of the authentication and re-association packets is lost, the handoff procedure will start from the beginning. It will take a long time before the SA starts over again. We refer that time as T_{wait}. The average handoff communication latency $T_{average\_handoff}$ is then derived as

$$
\begin{aligned}
&T_{average\_handoff} = \\
&(1-PLR)^2\{(1-PLR)^4 * [6 * T_{average}(r) + T_{process}] \\
&+ [1-(1-PLR)^4] * [6 * T_{average}(r) + T_{process} \\
&+ T_{wait}]\} + [1-(1-PLR)^2]\{(1-PLR)^4 * [6* \\
&T_{average}(r) + T_{process} + T_{period_probe}] + \\
&[1-(1-PLR)^4] * [6 * T_{average}(r) + T_{process} \\
&+ T_{period_probe} + T_{wait}]\},
\end{aligned} \tag{3}
$$

The rewards under different circumstances are defined as follows. When $H(k) = 0$ and $a_h(k) = M$, which means the

SA is associated with the old AP and no handoff happens, the reward under this circumstance is defined as

$$r(\varepsilon(k), \gamma 1(k), \gamma 2(k), \xi(k), H(k), a_h(k), a_r(k)) = \begin{cases} 1/(Q(\varepsilon(k) + \alpha * T + p * \alpha * T_{front\_average\_handoff})^2 \\ +Ru^2), \text{if } T < T_{average}, H(k) = 0, a_h(k) = M, \\ 1/(Q(\varepsilon(k) + \frac{u}{M} * T + p * \alpha * T_{front\_average\_handoff})^2 + \\ Ru^2), \text{if } T > T_{average}, H(k) = 0, a_h(k) = M, \end{cases} \quad (4)$$

where u is the control command from the ATO subsystem to bring the train to the optimized guidance trajectory, and α is the deceleration that defines the ATP service braking curve. When $T < T_{average}$, the current communication latency is greater than the communication period and the MA cannot be updated under this decision epoch. Therefore, the velocity tracking error is increased by $\alpha * T$ due to a communication interruption of T. As we can see from Fig. 1, for any train that is traveling behind, when the front train in front is in handoff state, it cannot receive the updated MA as well. This is because the train in front cannot report its new position to ZC. We assume the probability that the front train stays in handoff state is p. Then the velocity tracking error increased by the front train handoff is $p * \alpha * T_{front\_average\_handoff}$, where $T_{front\_average\_handoff}$ is the average handoff latency of the front train.

When $0 < H(k) < n_H$ and $a_h(k) = M + 1$, the SA is in handoff process, and the MA has not been updated for a time period of $H(k) * T$. The reward under this circumstance is defined as, $r(\varepsilon(k), \gamma 1(k), \gamma 2(k), \xi(k), H(k), a_h(k), a_r(k)) = 1/(Q(\varepsilon(k) + H(k) * T * \alpha + p * \alpha * T_{front\_average\_handoff})^2 + Ru^2)$, if $0 < H(k) < n_H, a_h(k) = M + 1$.

When $H(k) = N_H$ and $a_h(k) = M + 1$, the SA just finishes handoff process, and the MA is updated after a communication latency caused by handoff. The ATP service brake stops, and the ATO subsystem takes control of the train. The reward under this circumstance is defined as, $r(\varepsilon(k), \gamma 1(k), \gamma 2(k), \xi(k), H(k), a_h(k), a_r(k)) = 1/(Q(\varepsilon(k) + \frac{u}{M} * T + \alpha * T_{average\_handoff} + p * \alpha * T_{front\_average\_handoff})^2 + Ru^2)$, if $H(k) = 0, a_h(k) = M + 1$, where $T_{average\_handoff}$ is the average handoff communication latency under current state $\{\gamma 1(k), \gamma 2(k), \xi(k)\}$. The velocity tracking error is increased by $\alpha * T_{average\_handoff}$ due to a communication latency of $T_{average\_handoff}$ caused by handoff.

C. State Transition Probability

Given the current state, $s(k) = \{\gamma_1, \gamma_2, \xi, H, \varepsilon\}$, and the chosen action, $a(k) = \{a_h(k), a_r(k)\}$, the probability function of the next state, $s(k+1) = \{\gamma_1^{'}, \gamma_2^{'}, \xi^{'}, H^{'}, \varepsilon^{'}\}$, is given by

$$P(s(k+1)|s(k), a(k)) = P[\gamma_1^{'}|\gamma_1] * P[\gamma_2^{'}|\gamma_2] * P[\xi^{'}|\xi, a(k)] * P[H^{'}|H, a(k)] * P[\varepsilon^{'}|\varepsilon], \quad (5)$$

where $P[\gamma_1^{'}|\gamma_1]$ and $P[\gamma_2^{'}|\gamma_2]$ are the channel state transition probabilities for the two wireless links, respectively, $P[\xi^{'}|\xi, a(k)]$ is the currently used AP transition probability, $P[H^{'}|H, a(k)]$ is the handoff indicator transition probability, and $P[\varepsilon^{'}|\varepsilon]$ is the velocity tracking error transition probability. The channel state transition probabilities can be obtained from real field test data, which is described in Subsection III-B. Other state transition probabilities will be derived in the following.

Firstly, we derive the transition probability for the current used AP. Because the next used AP is determined by the chosen action, the currently used AP transition probability is simply derived as

$$P[\xi^{'}|\xi, a(k)] = \begin{cases} 0, & \text{if } a_h(k) \neq \xi^{'}, \\ 1, & \text{if } a_h(k) = \xi^{'}. \end{cases} \quad (6)$$

Secondly, we derive the transition probability for the handoff indicator. The handoff action determines the handoff indicator transition probability. When $H = 0$, which means that the SA is not in handoff process. $P[H^{'}|H, a(k)]$ is derived as,

$$P[H^{'}|H, a(k)] = \begin{cases} 1, & \text{if } a_h(k) = \xi^{'}, H^{'} = 0 \\ 1, & \text{if } a_h(k) \neq \xi^{'}, H^{'} = 1 \\ 0, & others. \end{cases} \quad (7)$$

When $H \neq 0$, which means that the SA is in handoff process. $P[H^{'}|H, a(k)]$ is derived as,

$$P[H^{'}|H, a(k)] = \begin{cases} 1, & \text{if } H^{'} = H + 1, \\ 1, & \text{if } H = N_h \ and \ H^{'} = 0, \\ 0, & others. \end{cases} \quad (8)$$

Lastly, we derive the transition probability for the velocity tracking error. The velocity tracking error is dependent on the control command at every decision epoch and the handoff action. Given a control command from the ATO subsystem to bring the train to the optimized guidance trajectory, the velocity tracking error transition probability is derived as

$$P[\varepsilon^{'}|\varepsilon, a(k)] = \begin{cases} 1, \text{if } H \neq 0, and \\ \varepsilon^{'} = \varepsilon + \alpha * T_{average\_handoff} + p * \alpha * T_{front\_average\_handoff}; \\ 1, \text{if } H = 0, T < T_{average}, and \\ \varepsilon^{'} = \varepsilon + \frac{u}{M} * T + p * \alpha * T_{front\_average\_handoff}; \\ 1, \text{if } H = 0, T > T_{average}, and \\ \varepsilon^{'} = \varepsilon + \alpha * T + p * \alpha * T_{front\_average\_handoff}; \\ 0, others, \end{cases} \quad (9)$$

where u is the control command, T is communication period, M is train mass, and α is the deceleration that defines the ATP service braking curve.

V. Simulation Results and Discussions

In this section, simulation examples are used to illustrate the performance of our CBTC system. We use C programming language to implement the value iteration algorithm to derive the optimal handoff decision and MIMO parameters adaption policy offline. We use NS2.29 simulator for our simulations to execute the optimal policy online. We consider a simulation scenario with three trains traveling between two stations. The wayside APs are deployed alone the railway line with an average distance of 600 meters between two successive APs. The three trains depart from the station A successively with interval Si and stop at the station B. Given a same trip time of 180 seconds, the ATO subsystems of the three trains all control the train to travel alone the same optimized guidance trajectory.

We compare the performance of our optimal SMDP policy with two other heuristic policies. For the first heuristic policy, the train SA makes handoff decisions based on the immediate reward, and the MIMO multiplexing gain is adapted to maximize

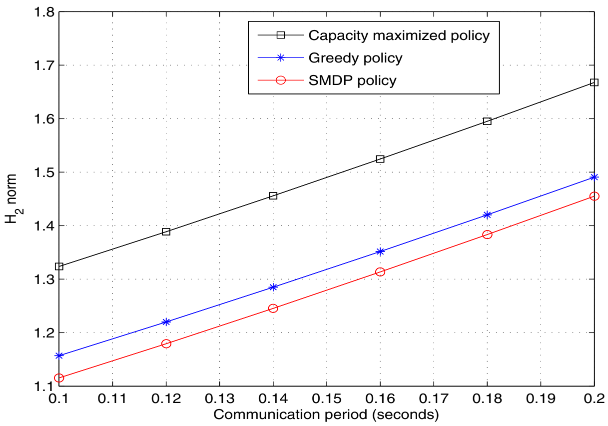

Fig. 3. The control performance H_2 norm under different policies.

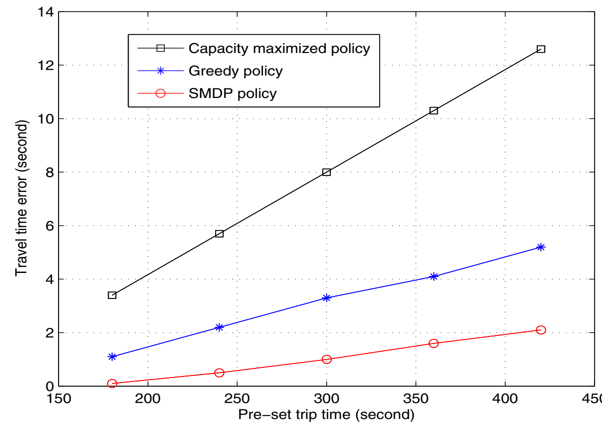

Fig. 4. The train travel time error under different policies.

the network capacity. We denote this policy as *capacity maximized policy*. For the second heuristic policy, we adapt physical layer multiplexing gain to minimize the linear quadratic cost for the train controller, but we make handoff decisions only based on the immediate reward, not the long-term reward. We denote this policy as *greedy policy*.

We first compare the train control performance H_2 norm in different policies. Recall that the square root of the linear quadratic cost performance measure is equivalent to the H_2 norm. We refer to the train control performance measure as the H_2 norm due to this equivalence. In this simulation scenario, the three trains depart from a station successively with interval $Si = 16s$, the deceleration α that defines the ATP service braking curve is set to be $1.2m/s^2$. As we can see from Fig. 3, our proposed SMDP policy gives the lowest H_2 norm compared to the other policies. This is because the optimization objective of the SMDP policy is to minimize the linear quadratic cost of train control, and it considers the dynamic transition of the wireless channel in CBTC systems, which helps the SA make optimal handoff and physical layer parameters adaptation decision to get the optimal performance.

Fig. 4 shows the error between the real travel time and the pre-set trip time for Train2 under different handoff decision policies. As shown in the figure, the travel time error is significantly increased when the trip time increases for the greedy policy and the capacity maximized policy. This travel time error severely affects the rail transit load capacity. By contrast, the train travel time under our SMDP policy is very close to the pre-set trip time. It successfully mitigates the wireless communication impacts on CBTC performance without decreasing the utilization of railway network infrastructure.

VI. Conclusions and Future Work

In this paper, in order to mitigate the impacts of wireless communications on CBTC performance, we took a cross-layer design approach to optimize the control performance in CBTC systems. Unlike the existing works that use traditional design criteria, such as network capacity and communication latency, we used linear quadratic cost for the train controller as the performance measure in the handoff design. Based on the channel state information, handoff decisions are made and physical layer MIMO parameters are adapted to optimize the train control performance. The problem was modeled as a Semi-Markov decision process (SMDP). Simulation results were presented to show that the proposed approach can significantly improve the train control performance, and increase the railway capacity. For future work, we plan to extend the proposed model to consider the train control policy. A jointly optimal train control and handoff decision policy will be derived from the extended model.

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