# A Dependable MAC Protocol Based on TDMA for Coexistence of Feedback-Control Systems

[1]Takahiro Goto, [2]Kento Takabayashi and [3]Ryuji Kohno,
[1]Graduate School of Engineering, Yokohama National University, Yokohama, Japan.
[2]Faculty of Computer Science and System Engineering, Okayama Prefectural University, Okayama, Japan;
[3]Faculty of Engineering, Yokohama National University, Yokohama, Japan.

***Abstract*****—**Wireless Networked Control Systems (WNCS) is attracting attention as a technology to realize to make efficient and reliable control systems utilizing wireless communication technologies. In particular, closed-loop feedback-control systems composed of a controller, sensors, and actuators, such as a glucose control system using an insulin pump for diabetes, are expected as important applications. Therefore, in order to guarantee high control quality, appropriate design of media access control (MAC) protocol to ensure low latency and reliability under coexistence of multiple feedback-control systems is required. This paper proposes a TDMA-based MAC protocol design utilizing the over-hearing scheme to satisfy such a requirement. The packet delivery rate is analyzed when the algorithm using over-hearing is executed. Moreover, the control quality performance of the WNCS system using proposal protocol is evaluated by computer simulation.

***Keywords*****—***Wireless Networked Control Systems, Feedback-Control Systems, Media Access Control, Time Division Multiple Access*

## I. INTRODUCTION

Recently, the concepts of the Internet of Things (IoT) and Cyber Physical Systems (CPS) are attracting much attention as one of paradigms of next-generation technologies [1]. This new paradigm is applied to a wide range of fields and applications such as industrial automation, medical systems, connected and automated vehicles, and so on [2], [3], [4]. Wireless Networked Control Systems (WNCS) play an important role in realization and performance improvement of such applications, and many studies have been made on this topic [5]. WNCS is often assumed to be composed of a controller and plants which have some sensors and actuators and to be performed wireless feedback control. Fig. 1 describes the conceptual diagram of wireless feedback-control system. The state quantities and the control commands corresponding to the state information are exchanged between the plants and the controller as shown in Fig. 1. State information measured by sensors of each plant is transmitted to the controller. Then, the controller calculates the appropriate command as control input and send the command to actuators in order to control the state of each plant. Since the sensor-controller and controller-actuator communication are performed via wireless network, it is difficult to avoid message loss and message delay which cause deterioration of control quality. Hence, it is required to design appropriate media access control (MAC) protocol to ensure low latency and reliability.

The studies of MAC protocol for WNCS can be classified roughly into contention-based access protocol and schedule-based access protocol. In contention-based access, such as carrier sense multiple access/collision avoidance (CSMA/CA) introduced in IEEE 802.11, each plant can try to get transmission opportunity at almost the same time as packet generation. Thus, throughput performance can be improved under unsaturated traffic conditions. However, the more the number of plants composing the network increase, the more the connections between the controller and plants become instable due to contention among plants. Moreover, since sampling, in general control systems, is performed periodically to a certain extent, adoption of contention process does not have enough effects. For such reasons, this paper focus on schedule-based access protocol represented by time division multiple access (TDMA).There have been several studies focusing on schedule-based access protocol for WNCS [6]-[10]. This paper proposes a MAC protocol based on TDMA using over-hearing scheme and shows that the proposal scheme can improve control quality performance of the wireless feedback-control system.

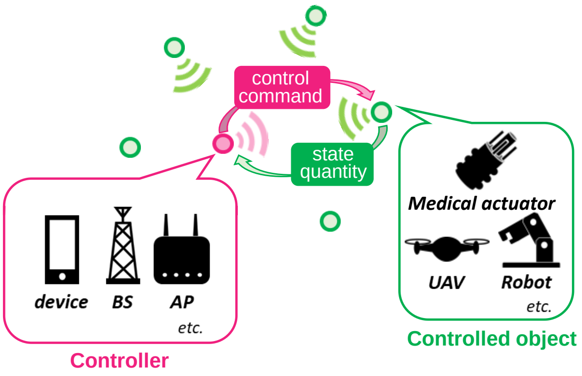

Fig. 1. Conceptual diagram of wireless feedback-control system

The rest of this paper is organized as follows. The system model and the scenario assumed in this study are described in Section 2. The concept and procedure of the proposed scheme are explained in Section 3. Section 4 shows performance evaluations by computer simulation and discussion of the simulation results. Finally, in last section, this paper draw a conclusion and future work.

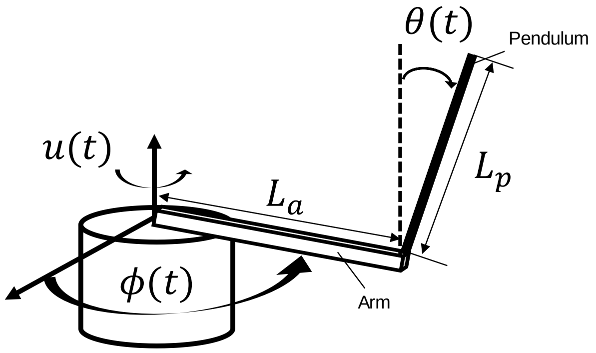

Fig. 2. Rotary Inverted Pendulum

## II. SYSTEM MODEL

This section describes the system models and scenarios assumed in this paper.

### *A. Controlled Object*

In this paper, a rotary inverted pendulum (RIP) system [11] is adopted as a controlled object. Moreover, the object is assumed to be linear time-invariant (LTI). Fig. 2 shows the diagram of the RIP model. The arm and the pendulum have lengths $L_a$ and $L_p$ , respectively. The angle of the pendulum $\theta(t)$and the angle of the arm $\phi(t)$are defined as function of time$t.\theta(t)$ is set to zero $(\theta(t)=0)$ in upright position and is positive when the pendulum rotates clockwise. The counterclockwise direction is defined as positive about$\phi(t)$. The state of the controlled object, in this study, is defined as

$$\boldsymbol{x}(t)=\left[\theta(t)\dot{\theta}(t)\ \phi(t)\dot{\phi}(t)\right]^T, \qquad (1)$$

then, by making linear approximation near $\theta=0$and using state space matrices $\boldsymbol{A}$ and $\boldsymbol{B}$, state equation can be expressed as [12], [13],

$$\dot{\boldsymbol{x}}(t)=\boldsymbol{Ax}(t)+\boldsymbol{Bu}(t)$$
$$=\begin{bmatrix} 0 & 1 & 0 & 0 \\ \dfrac{bd}{ab-c^2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ \dfrac{-cd}{ab-c^2} & 0 & 0 & 0 \end{bmatrix}\boldsymbol{x}(t)+\begin{bmatrix} 0 \\ \dfrac{-c}{ab-c^2} \\ 0 \\ \dfrac{a}{ab-c^2} \end{bmatrix}\boldsymbol{u}(t), (2)$$

where

$$a=J_p+m_p l_p^2, \qquad (3)$$

$$b=J_a+m_a l_a^2+m_p L_a^2, (4)$$

$$c=m_p L_a l_p, \qquad (5)$$

$$d=m_p l_p g, \qquad (6)$$

where $\boldsymbol{u}(t)$ is the torque input of the arm. $J_a$ and $J_p$ are themoments of inertia of the arm and the pendulum around the centers of them. $l_a$and $l_p$denote the distancesof the center of mass of the arm and the pendulum to the pivot points of them respectively. $m_a$ and $m_p$ are the masses of the arm and the pendulum. $g$ is gravitational acceleration.

### *B. Feedback-Control System*

The control system is discretized with the sampling period $T_s$ in order to perform digital control and then $k$ $(k=0,1,2,...)$ is used as discrete-time index. The block diagram of the discrete feedback-control system is shown as Fig. 3. Using matrices $\boldsymbol{A_d}=\exp(\boldsymbol{A}T_s)$ and $\boldsymbol{B_d}=\int_0^{T_s}\exp(\boldsymbol{A}\tau)d\tau\boldsymbol{B}$ , the state equation (2) can be rewritten as difference equation $\boldsymbol{x}[k+$ $1=\boldsymbol{Adx}k+\boldsymbol{Bdu}k$with assuming the zero-order hold input until the next sampling time.

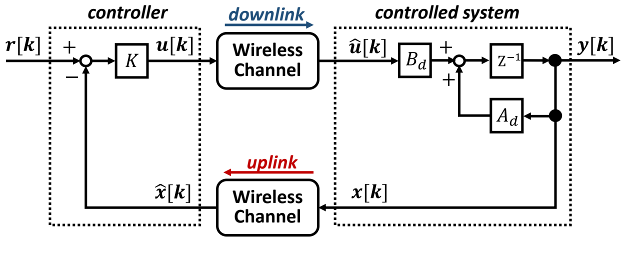

Fig. 3. The block diagram of the closed-loop feedback-control system

At the plants which have an actuator, a sensor, and a controlled object, state information measured by the sensor is transmitted to the controller as control output$\boldsymbol{x}[k]=\boldsymbol{x}(kT_s)$. When the plant get the received control command $\hat{\boldsymbol{u}}[k]$from the controller, the actuator performs according to the command in order to make the state values closer to the target. At the controller, a control command is calculated from deviation between the target value vector $\boldsymbol{r}[k]=\left[\Theta(kT_s)\dot{\Theta}(kT_s)\Phi(kT_s)\dot{\Phi}(kT_s)\right]^T$ and the received control output vector $\hat{\boldsymbol{x}}[k]$ which has the estimated values of the controlled object state. Then, the control command $\boldsymbol{u}[k]=\boldsymbol{u}(kT_s)$is derived by

$$\boldsymbol{u}[k]=\boldsymbol{K}(\boldsymbol{r}[k]-\boldsymbol{x}[k]), (7)$$

where$\boldsymbol{K}$ is the feedback gain and can be expressed as

$$\boldsymbol{K}=\boldsymbol{R}^{-1}\boldsymbol{B}^T\boldsymbol{P}, \qquad (8)$$

where $\boldsymbol{P}$ is the symmetric positive definite solution of the Riccati equation given by

$$\boldsymbol{A}^T\boldsymbol{P}+\boldsymbol{PA}-\boldsymbol{PBR}^{-1}\boldsymbol{B}^T\boldsymbol{P}+\boldsymbol{Q}=0, \qquad (9)$$

where $\boldsymbol{Q}$and $\boldsymbol{R}$ are weighting matrices and set as follows:

$$\boldsymbol{Q}=\begin{bmatrix} 8 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 0.4 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \qquad (10)$$

$$\boldsymbol{R}=[0.5], \qquad (11)$$

### *C. MAC Layer*

TDMA mechanism is adopted as a multiple access scheme. The controller has the responsibility to coordinate the plants, which have the controlled systems shown as Fig. 3, of the network. The time on the channel is divided into time slots called TDMA slots. Each plant of the network is allocated a TDMA slot in where it is allowed to transmit data packets. A TDMA frame is composed of TDMA slots whose number is generally the same as the number of plants connected to the TDMA network. The remaining period between the end point of the last TDMA slot and the initial point of the successive beacon or TDMA frame is called inactive period. All devices can sleep and save their energy consumption during inactive periods.

### *D. PHY Layer*

A WNCS is composed of a controller and multiple plants with star topology. Each plant has its transmitter and receiver and is able to communicate in wireless connections. Additive White Gaussian Noise (AWGN) is assumed to be the wireless channel environment. Bit-inversion can occurs on the transmitted signal due to the noise added to it.

## III. PROPOSED SCHEME

In this section, the concepts of the proposed scheme and its procedure are explained.

### *A. Overview of the ProposalScheme*

This paper propose to incorporate over-hearing mechanism

Into the conventional TDMA scheme for wireless feedback-control systems. Over-hearing, in this paper, is defined as a plant's reception of packets during a TDMA slot which is not allocated to the plant. In general, a plant can sleep and save its energy consumption during TDMA slots except for slots allocated to the plant. In the proposal scheme, however, a plant only can receive packets while the plant stays in a slot (here called "over-hearing slot") in which the plant is allowed to perform over-hearing. In this paper, it is assumed that the previous and next slots of the slot originally allocated to the plant are allocated as over-hearing slots. When a plant succeeded in reception of uplink (or downlink) packet during the previous slot for over-hearing of allocated TDMA slot for the plant and uplink (or downlink) communication for the previous plant in TDMA frame is failed, the plant can transmit the its own packet including the payload (here called "extra payload") of the received packet for the previous plant in order to recover the message loss. In the same way, the plant can be recovered its message loss by the next plant during the next slot for over-hearing.

### B. *Over-Hearing Operation*

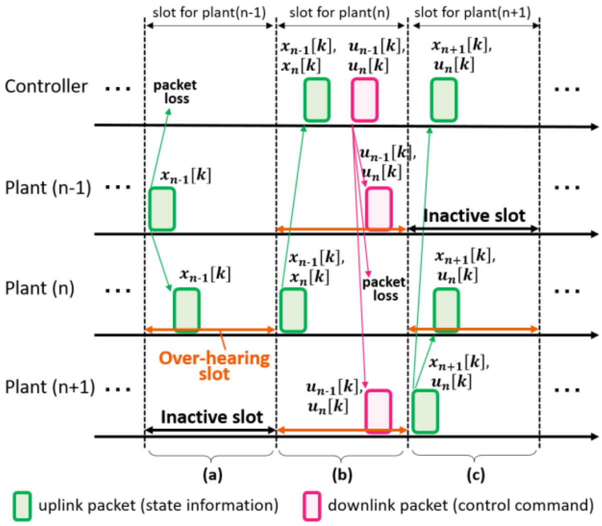

Fig. 4 Over-hearing operation.

The $plant(n)$,which is allocated the $n$th TDMA slot in the TDMA frame, can use those periods for over-hearing during TDMA slots for $plant(n-1)$ and $plant(n+1)$ as shown in Fig.4(a) and (c) respectively.

When the $plant(n-1)$ transmits state information $x_{n-1}[k]$ as the uplink packet, not only the controller but also $plant(n)$ can receive the packet. In Fig.4(a), only the $plant(n)$ succeeded in receiving the packet because packet loss occurred in uplink between the $plant(n-1)$ and the controller. Then, the $plant(n)$ added the state information received from the $plant(n-1)$ to the payload to be transmitted in the TDMA slot for the $plant(n)$as extra payload as shown in Fig.4(b). After the reception of the uplink packet from the $plant(n)$ , the controller derived the control commands $u_{n-1}[k]$ and $u_n[k]$ corresponding to $x_{n-1}[k]$ and $x_n[k]$ respectively and transmitted the commands as the downlink packet. However, the $plant(n)$ failed in reception of the packet as shown in Fig.4(b). Since the $plant(n+1$succeeded in reception of the downlink packet which the $plant(n)$ lost, the $plant(n+1)$ transmitted its own uplink packet including $u_n[k]$ as extra payload as shown in Fig. 4(c).

### C. *Extra Payload Determination*

Fig. 5 shows the flowchart of extra payload determination for the $plant(n+1)$. The $plant(n+1)$determines which extra payload to combine with its original payload corresponding to the result of communication in TDMA slot for the $plant(n)$as shown in the flowchart.

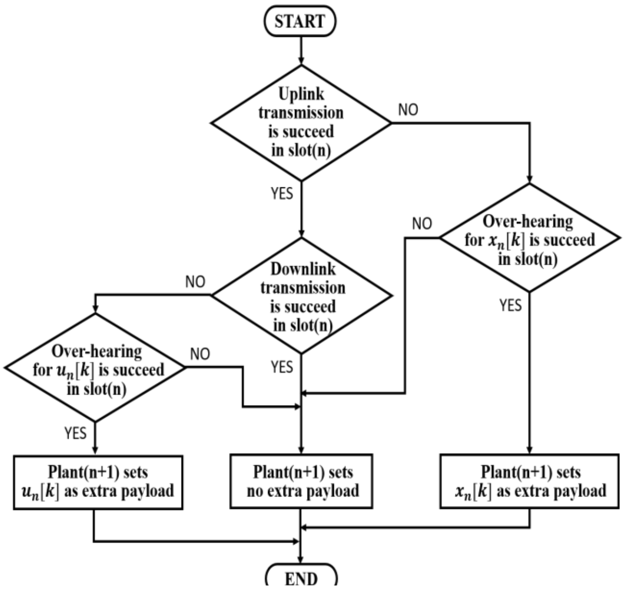

Fig. 5. Flowchart of extra payload determination

## IV. PERFORMANCE EVALUATION AND DISCUSSIONS

### A. *Condition of Evaluations*

In this section, some evaluations to confirm the dependability of the proposed scheme are performed.

TABLE I. PARAMETERS OF ROTARY INVERTED PENDULUM [14]

| **Parameter** | **Value** |
|---|---|
| Mass of the arm: $m_a$ | 0.080 kg |
| Mass of the pendulum: $m_p$ | 0.098 kg |
| Length of the arm: $L_a$ | 0.150 m |
| Length of the pendulum: $L_p$ | 0.215m |
| Moment of inertia of the arm around its center of mass: $J_a$ | $3.00\times 10^{-2}$kgm$^2$ |
| Moment of inertia of the pendulum around its center of mass: $J_p$ | $2.62 \times 10^{-3}$ kgm$^2$ |
| Length from the pivot of the arm to its center of mass: $l_a$ | 0.100 m |
| Length from the pivot of the pendulum to its center of mass: $l_p$ | 0.148 m |
| Gravitational acceleration: $g$ | 9.81 m/s$^2$ |

Table I shows the simulation parameters of the rotary inverted pendulum. The target value of the arm angle is changed between $-\pi/4$ and$\pi/4$ rad every 5 seconds.In this simulation, each plant has the same sampling period derived as the product of the number of plants and TDMA slot length. When even only one absolute value of plants' angle of pendulum exceed $\frac{\pi}{4}$rad, the pendulum is assumed to be fall-down.

Moreover, Table II shows wireless communication parameters. All plants and controller are assumed to be not hidden node each other.

### B. *Simulation Results and Discussions*

Here, the simulation results of the feedback control system based on proposed MAC protocol and conventional basic TDMA operation are described.

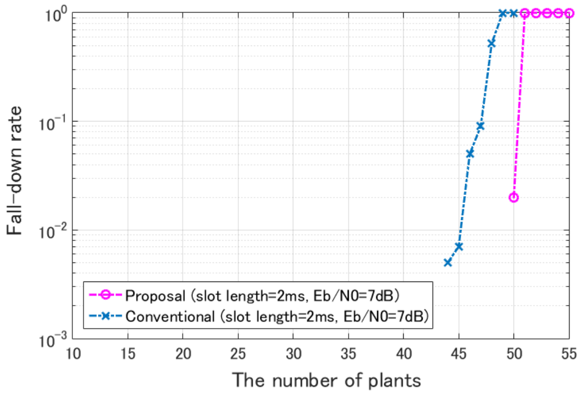

Fig. 6. The comparison of fall-down rate performance (Eb/N0=6dB)

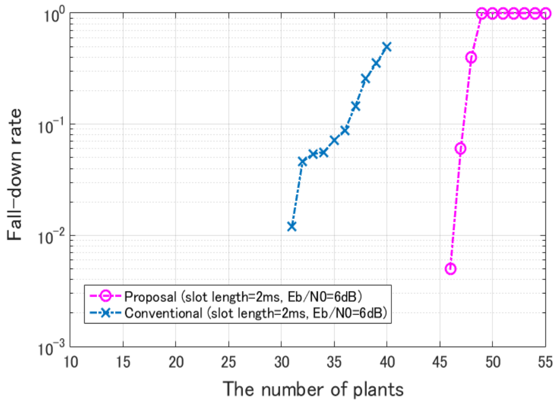

Fig. 7. The comparison of fall-down rate performance (Eb/N0=7dB)

Fig. 6 and Fig. 7 show the fall-down rate performance as a function of the number of plants with TDMA slot length of 2 msec. The proposal scheme simply shows good performance of fall-down rate as shown in Fig. 6 and Fig. 7. In addition, it is confirmed that the system using the proposal scheme has more capacity of the number of plants than the conventional scheme. From the deference of between fall-down rates of proposal in Fig. 6 and Fig. 7, the capacity may be expected around 50.

TABLE II. PARAMETERS OF WIRELESS COMMUNICATION

| Parameter | Value |
|---|---|
| Channel Model | AWGN |
| Modulation | BPSK |
| Symbole rate | 600 ksps |
| Multiple access scheme | TDMA |
| Simulation time | 60 s |
| TDMA slot length | 2 ms |
| Payload size (state information) | 4 byte |
| Paylod size (control command) | 1 byte |
| Header size | 10 byte |

## CONCLUSIONS

This paper proposed MAC protocol based on TDMA using the over-hearing method. Thus, the fall-down rate performance as control quality is evaluated using computer simulation and the performance of our proposal scheme is compared to the conventional scheme. From the numerical result, it is confirmed that our proposed scheme can make WNCS more dependable than the conventional scheme due to the effect of over-hearing.

For the future work, the power consumption performance should be studied. Moreover, also the case that each plan has deferent sampling periods should be addressed.

## *References*

[1] S.K. Khaitan and J.D. McCalley, "Design techniques and applications of cyber physical systems: a survey," IEEE Syst. J., vol. 9, no. 2, pp. 350-365, 2015.

[2] M. Wollschlaeger, T. Sauter and J. Jasperneite, "The future of industrial communication: Automation networks in the era of the Internet of Things and industry 4.0", IEEE Ind. Electron. Mag., vol. 11, pp. 17-27, 2017.

[3] S.M. Riazul Islam, D. Kwak, M. Humaun Kabir, M. Hossain and K.-S. Kwak, "The Internet of Things for health care: A comprehensive survey", IEEE Access, vol. 3, pp. 678-708, Jun. 2015.

[4] K.M. Alam, M. Saini and A.E. Saddik, "Toward social internet of vehicles: concept architecture and applications," IEEE Access, vol. 3, pp. 343-357, 2015.

[5] P. Park, S.C. Ergen, C. Fischione, C. Lu and K.H. Johansson, "Wireless network design for control systems: A survey," IEEE Commun. Surveys Tuts., vol. 20, no. 2, pp. 978-1013, 2018.

[6] J. Araujo, A. Anta, M. Mazo Jr., J. Faria, A. Hernandez, P. Tabuada, and K. H. Johansson, "Self-triggered control over wireless sensor and actuator networks," in IEEE International Conference on Distributed Computing in Sensor Systems, Barcelona, Spain, 2011.

[7] Y.S. Lee and S.H. Chung, "An efficient distributed scheduling algorithm for mobility support in IEEE 802.15.4e DSME-based industrial wireless sensor networks", Int. J. Distrib. Sensor Netw., vol. 12, no. 2, Jan. 2016.

[8] R. Moraes, F. Vasques and P. Portugal, "A tdma-based mechanism to enforce real-time behavior in wifi networks", the 7th IEEE International Workshop on Factory Communication Systems, pp. 109-112, may 2008.

[9] M. Anwar and Y. Xia, "TDMA based IEEE 802.15.4 for low latency deterministic networked control systems," 27th Chinese Control and Decision Conference, pp. 5270-5275, 2015.

[10] Y. Sadi, S. C. Ergen and P. Park, "Minimum energy data transmission for wireless networked control systems," IEEE Trans. Wireless Commun., vol. 13, no. 4, pp. 2163-2175, Apr. 2014.

[11] K. Furuta and M. Yamakita, "Swing up Control of Inverted Pendulum,"IECON'91, pp. 2193-2198, 1991.

[12] J. Akesson, K.J. Åström, "Safe Manual Control of the Furuta Pendulum, "Proc. of the 2001 IEEE International Canference on Control Applications, Mexico City, pp. 890-895, 2001.

[13] B.S. Cazzolato and Z. Prime, "On the dynamics of the furuta pendulum," Journalof Control Science and Engineering, 2011.

[14] Y. Baba, M. Izutsu, Y. Pan and K. Furuta, "Design of Control Method to Rotate Pendulum", Proceedings of the SICE-ICASE International Joint Conference, 2006.