

A Study on CBR-Based Adaptive Information Transfer for CSMA/CA-Based Coverage Control

Manato Washioka

Dept. Electrical and Electronic Engineering
Meijo University
Nagoya, Japan
253427030@ccmailg.meijo-u.ac.jp

Kentaro Kobayashi

Dept. Electrical and Electronic Engineering
Meijo University
Nagoya, Japan
kkobaysh@meijo-u.ac.jp

Abstract— In CSMA/CA-based coverage control, forwarding position information is expected to improve control performance. However, increasing the amount of forwarded information can cause packet collisions, making it crucial to set an appropriate transfer rate. In particular, in coverage control deployed from the center, the communication congestion state varies between the initial deployment phase and the final convergence phase; thus, a method using a single fixed transfer rate cannot consistently achieve optimal performance. To address this issue, this paper proposes an adaptive information transfer method that switches the transfer rate based on the Channel Busy Ratio (CBR), which represents the congestion level of the communication channel. Using a specific 80-agent environment as a baseline, we construct a function that takes the CBR as input and outputs the transfer rate. The obtained function is then directly applied to environments with 20 to 100 agents and compared with fixed transfer rate methods. The simulation results show that the proposed method achieves control performance comparable to those of the best fixed transfer rate methods across all evaluated environments. These results confirm that the CBR-based adaptive transfer method exhibits robust generality for environments with different numbers of agents.

Keywords—Wireless control, distributed control, coverage control, CSMA/CA, information transfer, channel busy ratio

I. INTRODUCTION

Autonomous decentralized control, in which a network is formed by multiple autonomous mobile agents that cooperatively operate through local information exchange, has attracted attention in the control field. Among such methods, coverage control is a type of autonomous decentralized control that aims to efficiently cover a given area with multiple agents. In coverage control, each agent determines its own assigned region based on the Voronoi partition and moves toward the centroid of that region, thereby achieving efficient coverage of the entire area [1, 2].

In autonomous decentralized control, wireless communication such as CSMA/CA is commonly used for information exchange among agents. However, when CSMA/CA is used, packet collisions can occur due to the hidden terminal problem and overlapping backoff times. These collisions cause the loss of position information from

neighboring agents, which degrades control performance. Information transfer is an effective approach to mitigating this problem [3], where each agent forwards received position information to neighboring agents, thereby compensating for the position information that could not be directly received.

Our previous study [4] investigated information transfer methods for coverage control and showed that, unlike in consensus control, complementing the position information of nearby agents is crucial. Based on this observation, the Near-First transfer method was proposed, in which the position information of nearby agents is preferentially included in the payload, and the optimal transfer rate was shown to depend on the number of agents. However, there is a trade-off: when the transfer rate is set too high, the packet size increases, which extends the channel occupancy time and can increase the packet collision rate.

Furthermore, in [5], we focused on a scenario in which agents are deployed simultaneously from a base station or a central location, and showed that the optimal information transfer rate differs between the high-density initial phase and the low-density final convergence phase. In that study, we investigated an adaptive information transfer method in which each agent changes the information transfer rate in stages based on the number of received packets observable by each agent. This method was effective in the scenario deployed from the center. However, the number of received packets is an absolute quantity that depends both on the number of agents in the environment and the communication conditions. Therefore, when the number of agents or environmental conditions change, parameter retuning is required. To achieve a more generalized method that is less dependent on environmental conditions, it is preferable to use an index that directly represents communication channel congestion rather than one that depends on the number of agents, such as the number of received packets.

This paper investigates an adaptive information transfer method based on the Channel Busy Ratio (CBR), which is widely used as an index of channel congestion in wireless communication systems such as V2X networks [6]. First, we analyze the relationship between the CBR and the information transfer rate in a specific environment to construct a CBR-transfer rate function. Then, this function is directly applied to environments with different numbers of agents, ranging from 20 to 100, and its generality under changes in the number of agents is evaluated.

A part of this research was supported by the Hibi Science Foundation, Japan.

II. CONTROL MODEL

This study considers coverage control in which multiple autonomous mobile agents move based on position information received from agents within their communication range and cooperatively cover a given area. In this section, we first formulate the autonomous decentralized control model used in this paper. We then describe the coverage control law and the CSMA/CA communication model used for information exchange among the agents.

A. Autonomous Decentralized Control Model

The dynamics of agent $i \in \{1, 2, \dots, N\}$ moving on a two-dimensional plane are represented by the following state equation:

$$\mathbf{x}_i[k+1] = \mathbf{x}_i[k] + \mathbf{u}_i[k], \quad \mathbf{x}_i[0] = \mathbf{x}_{0i} \quad (1)$$

Here, k denotes the discrete time index, $\mathbf{x}_i[k] \in \mathbb{R}^2$ is the position of agent i , and $\mathbf{u}_i[k] \in \mathbb{R}^2$ is the control input. Each agent determines its control input at every control period and moves within a maximum velocity constraint.

In practical systems, sensor noise must be considered in state observation. The observed position of agent i is expressed as

$$\mathbf{z}_i[k] = \mathbf{x}_i[k] + \mathbf{n} \quad (2)$$

where the observation noise follows a Gaussian distribution with mean zero and variance σ^2 .

At every control period, each agent observes its own position and exchanges position information with agents within its communication range R according to the CSMA/CA communication method described in Section II-C. Agents from which position information is successfully received during a control period are referred to as neighboring agents. The set of neighboring agents of agent i is denoted by $\mathcal{N}_i[k]$. Based on the position information received from these neighboring agents, each agent determines its control input using the coverage control law described in Section II-B.

B. Coverage Control

Coverage control is a type of autonomous decentralized control in which multiple agents efficiently cover a given area. Each agent autonomously determines its control input using position information received from other agents and moves toward its target point. In coverage control, each agent computes its Voronoi region based on its own position and the received positions of the other agents.

The control input of agent i at control period k is given based on the difference between its current position and the centroid of its Voronoi region, as follows:

$$\mathbf{u}_i[k] = -K(\mathbf{x}_i[k] - \mathbf{c}_i[k]) \quad (3)$$

Here, $\mathbf{x}_i[k]$ is the current position of agent i , $\mathbf{c}_i[k]$ is the centroid of the Voronoi region of agent i computed from the position information available to the agent, and K is the control gain. In this study, $K = 0.5$ is used.

C. CSMA/CA Communication Model

In this study, CSMA/CA is used for communication among agents. CSMA/CA is a communication protocol with a collision avoidance mechanism and is used in the IEEE 802.11 wireless LAN standard.

When an agent has a packet to transmit, it first senses the channel during the DIFS (Distributed Inter-Frame Space) period. If the channel remains idle during this period, the agent enters the backoff phase. In the backoff phase, each agent randomly selects an integer from $[0, CW]$, where CW is the contention window, and sets the backoff time as the product of this value and the slot time. This random waiting time reduces packet collisions caused by simultaneous transmissions. The backoff counter is suspended when another agent's transmission is detected and resumes after the channel becomes idle again.

Following this mechanism, each agent broadcasts a packet containing its own position information to agents within its communication range at every control period. When the information transfer method is applied, the packet also includes the transferred position information. The broadcast operation follows the IEEE 802.11 DCF broadcast mode. However, packet collisions caused by hidden terminals can occur. Unlike unicast communication, the broadcast communication considered in this paper does not use the RTS/CTS exchange or ACK-based retransmission, because multiple agents may receive the same broadcast packet simultaneously.

This study introduces the CBR as an index representing the congestion state of the communication channel. Let $N_{\text{obs},i}[k]$ be the total number of slots observed by agent i during a control period k , and let $N_{\text{busy},i}[k]$ be the number of slots in which the channel is sensed as busy because agent i is transmitting or at least one neighboring agent is transmitting. Then, the CBR of agent i is defined as follows:

$$CBR_i[k] = \frac{N_{\text{busy},i}[k]}{N_{\text{obs},i}[k]} \quad (4)$$

The CBR represents the channel occupancy around each agent at any given time, rather than the number of surrounding agents itself. In the proposed method, each agent adaptively switches its information transfer rate based on the observed CBR.

III. INFORMATION TRANSFER METHOD

This section describes the overview of the information transfer method for coverage control and the adaptive transfer strategy proposed in this paper.

A. Overview of Information Transfer

In coverage control, each agent requires the position information of surrounding agents to accurately compute its Voronoi region. However, due to packet collisions caused by the hidden terminal problem and constraints on the backoff time, communication with some agents may fail. This section describes an information transfer method to compensate for

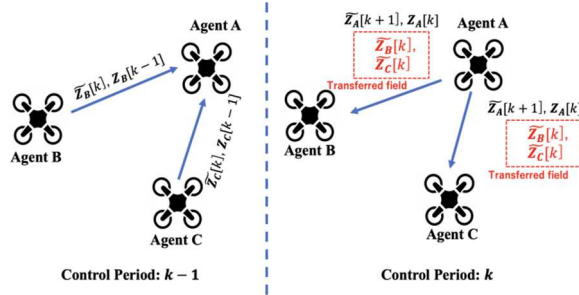


Fig. 1. Information transfer method.

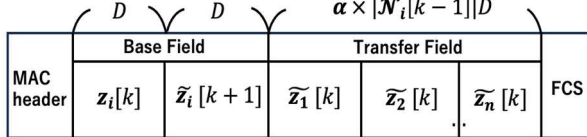


Fig. 2. Packet structure.

the missing position information caused by such communication failures.

Each agent includes not only its own position information but also part of the position information received from neighboring agents in its packet and forwards it. This enables an agent to indirectly obtain the position information of agents that could not be obtained through direct communication, thereby compensating for missing position information. In addition, each agent computes its predicted position in the next control period based on its current velocity and adds it to the packet in order to compensate for the time delay of its own position information, which is illustrated in Fig. 1. Therefore, the packet transmitted by each agent is structured as shown in Fig. 2. Here, the field containing information related to the transmitting agent itself is defined as the basic field, and the field containing the transferred information is defined as the transfer field.

The transfer rate α is introduced as a quantity representing how much of the received position information is forwarded. When determining the information to be forwarded using the transfer rate α , it is necessary to decide which received information should be included in the transfer field first. In this study, we adopt the Near-First transfer method, in which the position information of agents closer to the transmitting agent is preferentially included in the transfer field. This is because, in coverage control, the position information of nearby agents is particularly important for computing the Voronoi region [4].

B. Limitation of Fixed Transfer Rate

In the scenario deployed from the center considered in this study, all agents are located at a relatively high density immediately after the start of control, and each agent has many neighboring agents within its communication range. In this phase, if the transfer rate is set excessively high, the amount of information included in the transfer field increases, and the packet size becomes larger, which extends the channel occupancy time. As a result, packet collisions increase, and the amount of successfully obtained position information may instead decrease.

TABLE I. SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Control Period(T_s)	0.1[s]	Packet Header + FCS Length	28[byte]
Maximum Velocity(V_{max})	30[km/h]	Position Data Length (D)	64[byte]
Convergence Radius(δ)	1.0[m]	Transmission Rate	6[Mbps]
Communication Range(R)	100[m]	Slot Time	9[μs]
Noise Strength (σ)	2.0[m]	DIFS	34[μs]
Simulation Time	60[s]	CW	1023

On the other hand, as the agents disperse over time, the density of surrounding agents decreases, and the amount of position information directly obtained from neighboring agents also decreases. In this phase, the influence of packet collisions becomes relatively small, while the importance of compensating for missing position information through information transfer increases. Therefore, a relatively high transfer rate is considered to be effective.

Thus, in coverage control deployed from the center, the desirable transfer rate varies between the high-density initial phase and the low-density phase near convergence. Therefore, a method using a single fixed transfer rate throughout the entire control process may be effective in one phase but either excessive or insufficient in the other phase, making it difficult to consistently achieve optimal control performance.

C. CBR-Based Adaptive Transfer Control

To address the limitation of fixed transfer rates described in the previous subsection, this study proposes an adaptive transfer control method that switches the transfer rate according to the congestion level of the communication channel observed by each agent. As the index of congestion, we use the CBR observed by each agent.

In the proposed method, the transfer rate $\alpha_i[k]$ is determined by a function that takes the CBR observed by agent i at control period k as the input and outputs it:

$$\alpha_i[k] = f(CBR_i[k]) \quad (5)$$

Here, $f: [0,1] \rightarrow [0,1]$ is a monotonically non-increasing piecewise linear function, whose concrete form is constructed in Section IV-A (Fig. 3).

When the CBR is high, the channel is regarded as congested, and the transfer rate is set to a low value. On the other hand, when the CBR is low, the communication load is regarded as light, and the transfer rate is increased to prioritize the compensation for the missing position information.

The detailed derivation of this function and the corresponding evaluation results are described in Section IV.

IV. SIMULATION

This section evaluates the construction method and effectiveness of the proposed CBR-transfer rate function

through simulations. The simulation parameters are shown in Table I.

In this study, the error between the Voronoi centroid estimated by an agent based on the position information obtained through communication and the ideal Voronoi centroid is defined as the centroid error, and this value is used as the evaluation metric. The centroid error of agent i at time k , denoted by $e_i[k]$, is defined as follows:

$$e_i[k] = \|\hat{\mathbf{c}}_i[k] - \mathbf{c}_i[k]\| \quad (6)$$

Here, $\mathbf{c}_i[k]$ is the estimated Voronoi centroid computed from the position information obtained through communication, and $\hat{\mathbf{c}}_i[k]$ is the ideal Voronoi centroid computed from the position information of all agents. In this section, the average centroid error over all agents and all control periods is used for both function construction and performance evaluation.

In the following, we first describe the method used to construct the CBR-transfer rate function in an 80-agent environment. We then compare the proposed method with the fixed transfer rate methods in the same environment. Furthermore, we apply the obtained function to environments with different numbers of agents and evaluate its generality.

A. Construction of the CBR-Transfer Rate Function

This subsection describes the method used to construct the CBR-transfer rate function in an 80-agent environment. In this study, the CBR-transfer rate function is defined as a piecewise linear function, and a function that minimizes the centroid error is obtained by automatically searching for the points at which the slope changes. The hyperparameter optimization framework Optuna [7] is used for this search.

First, the CBR-transfer rate function is defined as a piecewise linear function with 10 slope change points. Each change point consists of b_n , which represents the position on the CBR axis, and α_n , which represents the transfer rate at that point. Both b_n and α_n are searched within the range $[0,1]$. In addition, based on the design policy that the transfer rate should decrease as the CBR increases, a monotonically decreasing constraint is imposed on the change points.

In each trial, a CBR-transfer rate function is generated based on b_n and α_n proposed by Optuna, and the function is applied to the simulation in the 80-agent environment. In the evaluation for each trial, 100 simulations are performed, and the average centroid error over all agents and all control periods in each simulation is calculated. Furthermore, the average value over the 100 simulations is used as the objective function value for that trial, and the search is performed so as to minimize this value. That is, the objective function J in the search is given using the centroid error $e_i[k]$ as follows:

$$J = \frac{1}{N_{\text{sim}}} \sum_{s=1}^{N_{\text{sim}}} \left(\frac{1}{NK_s} \sum_{k=1}^{K_s} \sum_{i=1}^N e_i^{(s)}[k] \right) \quad (7)$$

Here, N_{sim} is the number of simulations, N is the number of agents, and K_s is the number of control periods in simulation s .

In this study, 2000 trials are performed for this objective function, and the function that gives the smallest objective

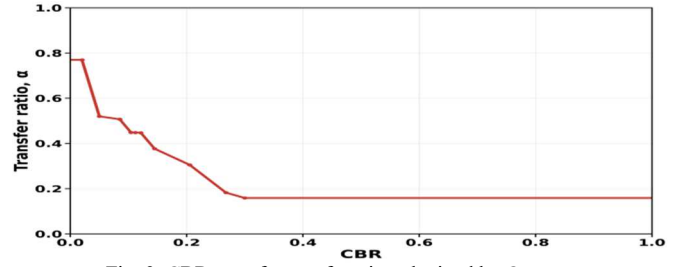


Fig. 3. CBR-transfer rate function obtained by Optuna. Change points: (0.02, 0.78), (0.05, 0.52), (0.08, 0.51), (0.10, 0.45), (0.11, 0.45), (0.12, 0.45), (0.14, 0.38), (0.21, 0.31), (0.27, 0.18), (0.30, 0.16), with linear interpolation between points and constant extension outside this range.

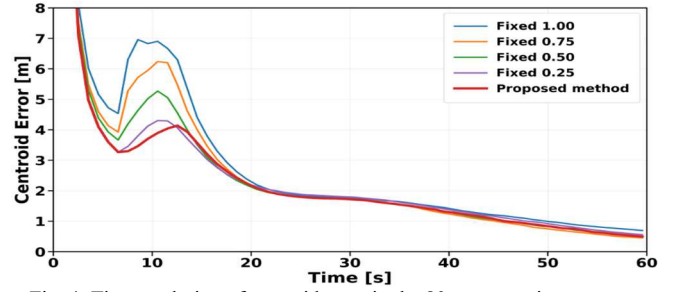


Fig. 4. Time evolution of centroid error in the 80-agent environment.

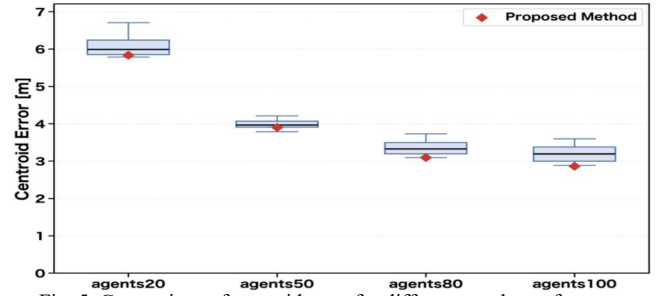


Fig. 5. Comparison of centroid error for different numbers of agents.

function value is adopted as the final CBR-transfer rate function. The obtained function is shown in Fig. 3.

B. Comparison with Fixed Transfer Rates in the 80-Agent Environment

This subsection applies the CBR-transfer rate function constructed in the previous subsection to the 80-agent environment and compares its performance with those of representative fixed transfer rate methods. Fig. 4 shows the time evolution of the centroid error in the 80-agent environment. The comparison targets are the proposed method and four fixed transfer rate methods with transfer rate fixed at 0.25, 0.50, 0.75, and 1.00.

In the fixed transfer rate methods, the communication load increases as the transfer rate becomes higher, and the centroid error tends to become larger, especially in the early phase of control. On the other hand, the proposed method shows a stably small centroid error throughout the entire time period. Even compared with the transfer rate of 0.25, which achieved the best performance among the four fixed transfer rates, the proposed method shows equivalent or better performance in many time periods. These results confirm that the CBR-transfer rate function obtained in the 80-agent environment

achieves higher control performance than those of the representative fixed transfer rate methods in the same environment.

C. Evaluation of Generality in Environments with Different Numbers of Agents

This subsection applies the CBR-transfer rate function constructed in Section IV-A directly to coverage control deployed from the center with 20, 50, 80, and 100 agents, and evaluates its generality by comparing its performance with those of the fixed transfer rate methods. Fig. 5 shows the variation in the centroid error of the fixed transfer rate methods and the result of the proposed method for each number of agents. In this figure, the boxplots represent the variation in the centroid error when 1000 simulations are performed for each fixed transfer rate from 0.01 to 1.00 in increments of 0.01, and the red diamonds indicate the results of the proposed method for each number of agents.

The results show that the proposed method achieves performance comparable to those of the best fixed transfer rate methods, especially in the 20-, 80-, and 100-agent environments. On the other hand, in the 50-agent environment, although there is a slight gap between the proposed method and the best fixed transfer rate method, the centroid error of the proposed method is smaller than the median of all the fixed transfer rate methods. Therefore, Fig. 5 demonstrates that the proposed method achieves a highly competitive performance among the fixed transfer rate methods.

The robustness of the proposed method can be interpreted as a negative-feedback mechanism for the communication load. When the number or local density of agents increases, more transmission attempts and longer channel occupancy raise the locally observed CBR. Because f is monotonically non-increasing, the increased CBR lowers the transfer rate, which reduces the amount of forwarded position information and shortens the packet duration, thereby mitigating channel occupancy and collision opportunities. Conversely, when the agents disperse and the channel becomes less congested, the CBR decreases and the transfer rate increases, allowing more of the missing position information to be compensated for through forwarding.

Unlike the number of received packets used in [5], the CBR is a normalized local measurement that reflects the aggregate communication load caused by the number of neighboring agents, their spatial distribution, and the packet duration. Therefore, the same CBR-transfer rate function can react to changes in the communication state without explicitly identifying the number of agents. This closed-loop adaptation explains why the function constructed in the 80-agent environment maintained competitive performance across the evaluated 20- to 100-agent environments, although it does not guarantee optimality under arbitrary communication or mobility conditions.

These results indicate that the obtained CBR-transfer rate function is not necessarily an optimal control rule for all environmental conditions. However, it can provide favorable performance without parameter retuning when the number of agents changes, and it is a practical control rule that shows sufficiently competitive performance at least in the 20- to 100-agent environments evaluated in this study.

V. CONCLUSION

This study investigated an adaptive information transfer method that switches the information transfer rate based on the CBR, which represents the congestion level of the communication channel, in CSMA/CA-based coverage control. First, a piecewise linear CBR-transfer rate function was constructed for an 80-agent environment using Optuna.

The simulation results showed that, in the 80-agent environment, the proposed method achieved superior performance in the time evolution of the centroid error compared with those of representative fixed transfer rate methods. In addition, even when the function constructed in the 80-agent environment was directly applied to environments with different numbers of agents ranging from 20 to 100, the proposed method showed performance comparable to those of the best fixed transfer rate methods in the 20-, 80-, and 100-agent environments. In the 50-agent environment, it also achieved better performance than the median of all the fixed transfer rate methods.

These results confirm that the CBR-based adaptive information transfer method exhibits robust generality across environments with different numbers of agents. Future work includes further optimizing the CBR-transfer rate function under more diverse conditions.

REFERENCES

- [1] J. Cortes, S. Martinez, T. Karatas, and F. Bullo, "Coverage control for mobile sensing networks," *IEEE Trans. Robotics and Automation*, vol. 20, no. 2, pp. 243-255, April 2004.
- [2] I. I. Hussein and D. M. Stipanovic, "Effective Coverage Control for Mobile Sensor Networks With Guaranteed Collision Avoidance," *IEEE Trans. Control Systems Technology*, vol. 15, no. 4, pp. 642-657, July 2007.
- [3] K. Kobayashi, R. Kimura, and W. Chujo, "Effectiveness of Information Transfer on Control Quality of CSMA/CA-Based Autonomous Decentralized Control," *IEICE Communication Express*, vol. 13, no. 2, pp. 18-21, Dec. 2023.
- [4] M. Washioka and K. Kobayashi, "A Study on Information Transfer Methods for CSMA/CA-based Coverage Control," *Proc. 2025 8th World Symposium on Communication Engineering (WSCE)*, pp. 26-30, Nov. 2025.
- [5] M. Washioka and K. Kobayashi, "A Study on Adaptive Control Information Transfer for Coverage Control Using CSMA/CA," *IEICE Technical Report*, vol. 125, no. 406, WBS2025-78, pp. 108-113, Mar. 2026 (in Japanese).
- [6] M. Sepulcre, M. Gonzalez-Martín, J. Gozalvez, R. Molina-Masegosa and B. Coll-Perales, "Analytical Models of the Performance of IEEE 802.11p Vehicle to Vehicle Communications," *IEEE Trans. Vehicular Technology*, vol. 71, no. 1, pp. 713-724, Jan. 2022.
- [7] T. Akiba, S. Sano, T. Yanase, T. Ohta, and M. Koyama, "Optuna: A Next-generation Hyperparameter Optimization Framework," *Proc. 25th ACM SIGKDD Int. Conf. on Knowledge Discovery & Data Mining (KDD)*, pp. 2623-2631, July 2019.