Adaptive Transmission Probability for CSMA/CA-Based Consensus Control of Multi-Agent Systems

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\textbf{Abstract:} This paper deals with consensus control for multi-agent systems over CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance)-based wireless networks. In consensus control, the number of agents within the communication range changes with time according to the movement of the agents and affects the packet collision rate. In this paper, we propose a new method to reduce the packet collision rate considering consensus dynamics of the agents. In the proposed method, each agent distributedly estimates the priority of its own position information on the basis of position information received from its adjacent agents and then adjusts transmission probability according to the estimated priority. Simulation results show that the proposed method improves the control quality.

\textbf{Keywords:} Wireless control, multi-agent systems, consensus control, CSMA/CA, packet collision

\textbf{Classification:} Wireless communication technologies

\textbf{References}

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1 Introduction

Coordinated control of autonomous mobile robots has been attracting attention in many industrial fields. Multi-agent system is one of control systems to realize such a coordinated control system, and is a distributed control system that consists of autonomous agents and whose behavior is determined by interaction between the agents. Consensus control that converges each agent’s state to a certain consensus state only by exchanging information with adjacent agents has been treated as a basic control problem of multi-agent system. When wireless communication is used for exchanging information among the agents in consensus control, the degradation of control quality due to communication failure becomes a problem.

Most research have been conducted to design control methods to reduce the influence of communication failure, e.g. [1–3]. The communication failure in these studies is assumed to occur with a constant probability. However, considering that the agents move toward a consensus position, the communication failure probability changes because the number of agents in the communication range changes with time, and the probability of collision of transmitted packets also changes. Therefore, for the improvement of control quality, it is necessary to reduce packet collision considering the movement of the agents. From this viewpoint, [4] has proposed a slotted ALOHA-based communication method and shown that setting of transmission probability based on the number of adjacent agents can reduce packet collision and improve the control quality.

In this paper, for CSMA/CA-based wireless consensus control, we propose a method to set transmission probability on the basis of estimated importance of agent’s position information, and show that the proposed method can reduce the packet collision rate and improve the control quality.

2 System model

This paper deals with an average consensus control problem [5] in which multiple autonomous mobile agents move on the basis of position information acquired from adjacent agents within a communication range and get together to a consensus position, namely, the average of their initial positions.

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\begin{align}
\mathbf{x}_i[k + 1] &= \mathbf{x}_i[k] + \mathbf{u}_i[k], \quad \mathbf{x}_i[0] = \mathbf{x}_0i, \tag{1}
\end{align}

where \(\mathbf{x}_i[k]\) and \(\mathbf{u}_i[k]\) are two-dimensional vector and represents position information and control input at time \(t = kT_s\) (\(T_s\): control period), respectively. \(\mathbf{x}_0i\) is the initial position. Each agent linearly moves in a two-dimensional plane at a constant speed not exceeding the maximum moving speed \(v_{\text{max}}\).

The network among the agents changes with time because of the movement of the agents and communication failure due to packet collision. The network at time index \(k\) is defined by a directed graph \(G[k] = \{V,E[k]\}\), where \(V = \{1,2,\ldots,N\}\) is a set of agents that compose the graph and \(E[k] = \{(i,j) \in V \times V\}\) is a set of agents with a communication path. The communication range of each agent is defined by radius \(R\). When communication from agent \(j\) to \(i\) is successful within the control period, i.e., \((j,i) \in E[k]\), agent \(j\) is defined as adjacent to \(i\). All adjacency relationship are represented by an adjacency matrix \(A[k] = [a_{ij}[k]] \in \{0,1\}^{N \times N}\), where \(a_{ij}[k] = 1\) if the agent \(j\) is adjacent to \(i\) and 0 otherwise. Adjacent agents of agent \(i\) are defined by \(\mathcal{N}_i[k] = \{j \in V|(j,i) \in E[k], i \neq j\}\), which is a set of agents where the agent \(i\) is adjacent.

\subsection{Consensus control}

The control input \(\mathbf{u}_i[k]\) of agent \(i\) is given by (2) using the deviation of its own position \(\mathbf{x}_i[k]\) and the position \(\mathbf{x}_j[k]\) received from adjacent agents.

\begin{align}
\mathbf{u}_i[k] &= \frac{-1}{|\mathcal{N}_i[k]| + 1} \sum_{j=1}^{N} a_{ij}[k](\mathbf{x}_i[k] - \mathbf{x}_j[k]), \tag{2}
\end{align}

where \(|\mathcal{N}_i[k]|\) is the number of adjacent agents. This results that each agent moves to the center of gravity of the positions. A consensus is achieved by distributedly determining the control input every control period. As described in (3), the consensus means that from any initial positions \(\mathbf{x}_{01}, \mathbf{x}_{02}, \ldots, \mathbf{x}_{0N}\), positions of all agents asymptotically converge the average \(\mathbf{x}_0\) of the initial positions.

\begin{align}
\lim_{k \to \infty} \mathbf{x}_i[k] = \mathbf{x}_0 = \frac{1}{N} \sum_{i=1}^{N} \mathbf{x}_{0i} \tag{3}
\end{align}

\subsection{CSMA-based transmission}

Agents transmit and receive position information to and from adjacent agents by broadcast communication using CSMA/CA. Each agent sends its own position information every control period. Then, the control input is determined on the basis of the position information received within the control period, and the agent moves according to the control input.

The operation of CSMA/CA is as follows according to the specification of IEEE802.11DCF broadcast communication. First, carrier sensing is performed, and if a signal is not detected on a channel for a \(DIFS\) duration,
data is transmitted after a backoff time elapses. This backoff time is given by $Random \times SlotTime$, where $Random$ is an integer random number distributed uniformly in $[0,CW]$, and $CW$ is a contention window value. The backoff suspends when the channel is sensed busy and resumes only after the channel is sensed idle for $DIFS$ duration again. Packet collision occurs when agents with the same backoff time simultaneously transmit position information. In addition, packet collision may occur due to hidden terminal problem. Such packet collisions cause degradation of the control quality.

3 Proposed method

In order to reduce packet collision, we propose a method in which each agent estimates the importance of its own position information at each control period, and permits transmission of the position information with a probability according to the importance. It is expected that the packet collision rate is reduced by less important agents stopping transmission, and thus the control quality can be improved.

3.1 Priority of position information

The agent’s position information close to the consensus position is highly important and should be sent. However, each agent can only obtain position information from adjacent agents and can not know where it is located in the whole system. The closeness to the consensus position needs to be estimated. For this reason, each agent uses distance $d_i[k]$ between the center of gravity of the adjacent agents in the previous control period and its position as a measure of the closeness to the consensus position.

$$d_i[k] = x_i[k-1] - \frac{1}{|N_i[k]|} \sum_{j=1}^{N} a_{ij}[k-1]x_j[k-1] \quad (4)$$

This takes advantage of the system dynamics of (1) and (2) and the fact that agents far from the consensus position often have a biased distribution of adjacent agents. As shown in Fig. 1, as $d_i[k]$ is smaller, the importance is higher because it is closer to the consensus position, and as $d_i[k]$ is larger, the importance is lower because it is farther from the consensus position.

![Fig. 1: Priority of position information](image-url)
| Parameters                   | Values       | Parameters           | Values       |
|------------------------------|--------------|----------------------|--------------|
| Control period \((T_s)\)    | 20 [ms]      | Data rate            | 11 [Mbps]    |
| Maximum speed limit \((v_{max})\) | 10 [m/s]    | Slot Time            | 20 [µs]     |
| Communication range \((R)\) | 150 [m]      | DIFS                 | 50 [µs]     |
| Radius of convergence \((\delta)\) | 50 [m]  | CW                   | 1023         |
| Simulation time              | 100 [s]      | Preamble length      | 40 [µs]     |
| The number of simulation     | 1000         | Data length          | 2048 [byte] |

### 3.2 Setting of transmission probability

The proposed method allows transmission with probability according to the measure \(d_i[k]\) of the importance of position information. The transmission permission probability \(P_t[k]\) is set as follows so that less important agents stop transmission of position information.

\[
P_t[k] = 1 - \frac{d_i[k]}{R}
\]

This means that the transmission probability is set linearly according to \(d_i[k]\) normalized with the maximum value \(R\). Within the control period, only agents that are probabilistically permitted to transmit will transmit its own position information.

### 4 Numerical examples

#### 4.1 Simulation setup

The effectiveness of the proposed method is evaluated by computer simulation. The simulation is set to control mobile agents like drones and parameters of IEEE802.11DCF are set with reference to [6]. The simulation parameters are shown in Table I. \(N = 100\) agents are uniformly randomly arranged in an area of 300[m] × 300[m]. Initial positions where the graph of network is disconnected and there is no possibility of achieving consensus are excluded beforehand. Performance evaluation has been conducted on several simulation parameters for the number of mobile agents, communication range; however, due to the limitation of space, here we show only numerical results where the effect of packet collision is remarkable.

The communication quality is evaluated by the average of packet collision rate. The quality of consensus control is evaluated by the average of the number of convergence agents. The number of convergence agents is defined as the number of agents located at a distance \(\leq \delta\) from each agent. In the evaluation, we compared the proposed method and the conventional method that permits transmission of all agents. In addition, in control quality evaluation, we also compared with the ideal performance where all agents in the communication range communicate without packet collision and therefore obtain all position information of adjacent agents.

#### 4.2 Simulation results

Figure 2(a) shows temporal changes of the packet collision rate. In the initial position, the packet collision rate is high because the number of hidden
terminal agents is large. Since the number of agents in the communication range increases as the agents approach the consensus, the number of hidden terminal agents decreases, and thus the packet collision rate decreases. The proposed method can reduce the packet collision rate in the range from the initial position until all agents are within the communication range of each other. Packet collision occurs even in the area after all agents have entered each other’s communication range, but this is caused by setting the same backoff time and transmitting simultaneously.

Figure 2(b) shows temporal changes of the number of convergence agents. As shown in Figure B, the proposed method converges faster than the conventional method. This is because the packet collision rate can be reduced and the number of agents that can communicate is increased. Further performance improvement is expected by a more appropriate function instead of the simple function (5).

5 Conclusion

In this paper, for consensus control of multi-agent system, we propose a method to reduce the packet collision rate by estimating the importance of agent’s position information and setting the transmission probability on the basis of the estimated importance. By computer simulation, it was shown that by suppressing the transmission of less important agents, the packet collision rate can be reduced and the control quality can be improved.

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