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CSMA/CD-R for a Wireless Multi-robot Commuication

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Abstract: This paper proposes a CSMA/CD-R (Carrier Sense Multiple Access/Collision Detection with Reservation) protocol, designed for wireless network mobile robots under a distributed robot system without any centralized mechanism. It employs stations to reserve a communication channel after communication collision for the wireless communication of the distributed robot system. The effectiveness and applicability of the proposed protocol are demonstrated by carrying out computer simulations and real experiments with the develped multi-robot system.

1. INTRODUCTION

The objective which develops a mobile robot system is to reduces the necessity of the person in minimum from a dangerous place which are, for example, to dispose the dangerous waste, repair the nuclear power plant, explore the different planet, rescue the people, search building or the dangerous area. And simple, repeat works, for example, automation production facility or the factory equipment maintenance are fields where the mobile robot system is necessary. From the view point of communication and cooperation, the research in the robot field can be divided into two categories, one using explicit communication and cooperation and the other not using them (implicit cooperation). First of all, in order to cooperate explicitly, the robot system knows the existence of other robots and cooperates with them through communication. This explicit and direct communication was addressed by L. Parker. In the case of implicit cooperation, a robot does not recognize other robots and cooperates implicitly with other robots which share the same purpose.

Each communicative robot is able to accomplish not only a task autonomously, but also a task which is impossible for a non-communicative robot. Thus, lots of current researches have been focused on the communicative robot system.

There are two representative communication methods widely used in multi-robot cooperation system, a time division multiplexing and a frequency division multiplexing. In a time division multiplexing, the token ring method and carrier sense multiple access (CSMA) method are representative communication methods for multi-robot cooperation system. On the other hand, in frequency division multiplexing, every robot is allocated with frequency resources but the communication channel is limited, so when the robot system size becomes larger, it becomes less applicable. In efficiency, the token ring method is superior. However, when only a robot breaks down, the next robot does not share information. Also, because it gives a communication ID to the robot and pass over the right of use of a channel sequentially, it does not support system the scalability in the sense of adding or removing a robot. So, comparatively, the CSMA method is more proper for a distributed robot system.

However, since the CSMA protocol was originally developed for Ethernet, it can not be operated over a wireless communication network for a distributed robot system. Existing variations of CSMA based on a centralized mechanism to detect and indicate a collision cannot be used because neither centralized mechanism nor ground support is allowed. To solve the problem above, this paper proposes a medium access protocol, CSMA/CD-R (Carrier Sense Multiple Access/Collision Detection with Reservation), for wireless network of mobile robots in a truly distributed robot system (i.e., without a centralized mechanism). It allows stations to reserve a channel after collision and by this reservation it can make a successful transmission in wireless communication among robots. The effectiveness and applicability of the proposed protocol are demonstrated through computer simulations and real experiments with the developed multi-robot system which is implemented to accomplish the waste cleanup mission.

This paper is organized as follows. In Section 2, the mechanism of the CSMA/CD-R protocol is proposed. In Section 3 and 4, a discrete event computer simulation and the experimental results are described. Summary and conclusions follow in Section 5.

2. WIRELESS MEDIUM ACCESS PROTOCOL

2.1 Assumptions and definitions

In this section, related assumptions and notions are described before proposing the CSMA/CD-R.

Assumption 1: Consider a distributed robot system, in which a generic communication system is implemented on every robot and auxiliary device such as a relay computer is not

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allowed. Existing CSMA protocol is designed to control a channel from a centralized communication server. In this paper, it is modified for use in a distributed robot system.

Assumption 2: All communication systems are half-duplex, where transmission and reception are both possible but not carried out simultaneously. This limitation is common for off-the-shelf wireless communication system. Because it cannot receive during transmission simultaneous, an external switch between transmission and reception is needed.

Assumption 3: Only one communication channel is allowed for communication among robots because most of offthe-shelf communication modules are fixed at a specific frequency and also the frequency resource is limited.

Assumption 4: The size of transmission data packet is fixed, and data from a robot can be distinguished from that transmitted by the others. When communication packets sent simultaneously by more than two robots are received, they cannot be distinguished and would be treated as a noise.

A mobile robot constitutes a *node* (or a *station*) of the wireless communication network. A single radio communication channel is used as a multi access medium shared by all nodes. Only one node should transmit at any given time. Simultaneous transmissions by more than one node cause a *collision*.

Consider a slotted system whereby time is divided into fixed length intervals. Each of these time intervals is called a *slot*. The purpose of the slotted system assumption is to simplify the explanation and simulation of the proposed protocol.

Let T be the duration of a slot. All stations in the network are synchronized so that a packet transmission always starts at the beginning of a slot. Henceforth, the concept of a slot is employed to refer also to the amount of data [bits] which can be transmitted within a time slot. Packet length may be variable, but it must be padded as in Ethernet so that it is equal to an integer number of slots.

Let τ denote the maximum propagation delay between any two stations in the network and the minimum duration of a slot is $T = 2\tau$. In addition, the channel is sensed idle by all stations τ units of time after the end of a successful transmission, and a successful transmission is detected τ units of time after it is started.

2.2 Carrier Sense Multiple Access/Collision Detection with Reservation (CSMA/CD-R)

A single radio communication channel is used as the raw medium for all nodes. To reduce the probability of simultaneous transmission (collision), a node checks the status of the shared communication channel before a transmission is attempted. If the channel is busy, it waits for a random period of time.

There is nevertheless still a small chance for two or more nodes to start transmission at almost the same time, which results in a collision. Due to strong radio energy emitted by the transmitter, it is impossible for a node to detect and realize that a collision has occurred until the transmission is completed.

To solve this problem, a novel wireless communication protocol, CSMA/CD-R (Carrier Sense Multiple Access/Collision Detection with Reservation) is proposed as shown in Figure 1.

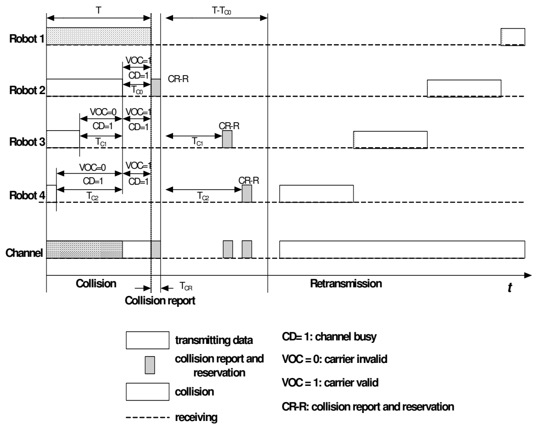

Fig. 1. Example of CSMA/CD-R

- CD (Collision Detection): it defines the status of a communication channel.

$$CD = \begin{cases} 1 & \text{if a channel is used by more than one node,} \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

- VOC (Validity of Carrier): it defines the validity of a communication channel. The received signal is valid if modulated signal from the transmitter can be demodulated (i.e. the received signal must have been emitted from a single node).

$$VOC = \begin{cases} 1 & \text{if a signal from the transmitter can be demodulated,} \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

- $CR-R$ (Collision Report with Reservation): an acknowledgement signal from nodes after collision. By this signal, a robot can decide the order of priority in re-transmitting.
- T_{cn}: a duration time from the transmission of a robot to the reception of a valid signal (a signal from a single robot). n is an order which recently finishes the transmission. The last robot to finish a transmission cannot recognize a collision, so it measures T_{cn} after the transmission of a robot which finishes a transmission second to the last.

Our proposed CSMA/CD-R protocol is an extension of the CSMA/CD protocol which has the following rules:

(1) If the channel is sensed idle ($CD = 0$), a ready node transmits its packet immediately. It is required to monitor the channel status in case of a collision.
(2) If the channel is sensed busy ($CD = 1$), a ready node keeps monitoring the channel status.

There is nevertheless still a small chance for two or more nodes to start transmission at almost the same time, which results in a collision. After detecting a collision, its packet should be retransmitted. By CSMA/CD-R protocol, the following rules are proposed for the collision:

(1) After transmitting a packet, if a packet is received, it is assumed to be collided.
(2) With a collision, if a signal is from more than two nodes, it cannot be translated ($VOC = 0$). In this case, T_{cn} can be measured, which is a duration time from the transmission of a robot to the reception of a valid signal (a signal from a single robot).
(3) With a collision, if a signal is from a node, it can be translated ($VOC = 1$). In this case, a collision report ($CR - R$) should be transmitted after a collision.

(4) After a collision (after receiving a $CR - R$), each node involved in a collision transmits a $CR - R$ in T_{cn}.
(5) After $(T - T_{c0})$, each node transmits its packet according to a sequence of transmitting a $CR - R$ (i.e. a node which transmits a $CR - R$ later, transmits its signal first). A node which receives n $CR - R$ after it sends a $CR - R$, transmits its signal at $n + 1$ turns. The last robot to finish a transmission, which transmits no $CR - R$ and receives n $CR - R$s, transmits its signal at $n + 1$ turns.

Figure 1 shows that four nodes (Robot1, Robot2, Robot3, Robot4) transmit simultaneously (collision). Each node checks a communication channel after a transmission. If a channel is used after a transmission ($CD = 1$ as shown in Figure 1), it is known that a collision has happened and other node is transmitting a signal simultaneously. However, a node which transmits a signal latest cannot recognize whether a collision has happened or not. Thus, the other node has to send a collision report by which a latest node knows about a collision. In Figure 1, Robot2 recognizes that a communication channel is used by another node after it finishes a transmission and switches a communication module from a transmission mode to a reception mode. Then, a validity of channel, VOC, should be checked. Since a signal which is received through a channel can be translated, it may be considered as a signal from a single node and in this case, VOC becomes 1. However, when Robot3 checks a communication channel after a transmission, it is known that Robot1 and Robot2 transmit simultaneously and a collision happens. Thus, if a received signal can be translated, i.e. it is different from pre-determined communication protocol, it means that more than two nodes are transmitting signals simultaneously and VOC equals zero. As already mentioned, a latest node which transmits a signal latest (Robot1 in Figure 1), cannot recognize a collision, so the second latest node (Robot2) should send a collision report, $CR - R$, which is a pre-defined signal for the latest node (Robot1) to recognize a collision.

Each node which collides with others, measures a duration time, T_{cn} (a period during which $VOC = 0$) from a collision. In Figure 1, each node waits for T_{cn} after Robot2 sends a collision report and then sends its $CR - R$ and then counts which number of received $CR - R$ is. Robot3 waits for T_{c1} after receiving a first $CR - R$, and sends its second $CR - R$. Robot4 waits for T_{c2} after receiving a first $CR - R$, and sends its third $CR - R$. Because there is no more $CR - R$ while all nodes wait for $T - T_{c0}$, the latest node, Robot4 which did not receive a $CR - R$ after it sent its $CR - R$, knows that it has a priority over other nodes and transmits a communication packet first. Then, Robot3 (received a $CR-R$ after it sent its $CR-R$), Robot2 (received two $CR - R$s after it sent its $CR - R$) and Robot1 (received three $CR - R$s) transmits its communication packet with its priority, explained in the rule (5).

With this CSMA/CD-R protocol, all nodes can arrange for $T - T_{c0}$ and retransmit after any collision.

There are several merits in proposed communication protocol as listed below.

- An existing wireline centralized communication protocol, CSMA/CD is modified for a wireless communication protocol for a distributed robot system.
- This CSMA/CD-R communication protocol is suited for a distributed robot system, because no external and central device is needed. This implies maintaining robustness which is a major merit of a distributed robot system.

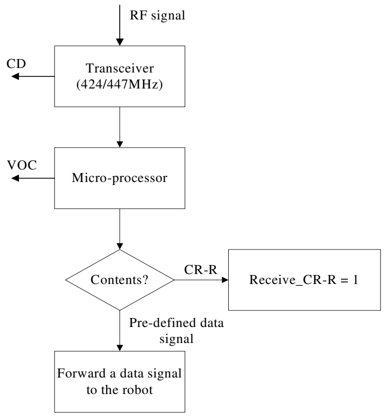

Fig. 2. Flow chart of a receive process

- From the viewpoint of scalability, a specific number or any way for identification is not used when each node uses a communication channel. Any node can use a communication channel at anytime and a robot can be added or removed without any bad influence on the distributed robot system. Theoretically, this protocol supports unlimited scalability.
- After a collision, it is possible for each node to retransmit its signal according to a priority scheme (First In First Out), so the proposed CSMA/CD-R protocol is superior to CSMA/CD.
- Since a CSMA/CD-R is an asynchronous protocol, the external synchronization signal is not necessary.

2.3 *Design of protocol*

A receive process checks the signal from the communication module. It analyzes the received signal to determine if it is a pre-defined data signal or a collision report ($CR - R$). Figure 2 shows a flow chart for the receive process.

If the received signal has a pre-defined frequency (424MHz in this paper), the status of a channel can be decided with a carrier detect (CD) of a communication module, busy ($CD = 1$) or idle ($CD = 0$).

If the signal is sent to a micro-processor and has a pre-defined protocol, it is forwarded to the next process with VOC set to 1. If a collision report, $CR-R$ or a noise is received , VOC is set to 0. Then the signal should be determined whether it is a signal packet or a $CR - R$. If a signal packet is received, a necessary data is extracted and forwarded to the robot. If a $CR - R$ is received, the $Receive\_CR - R$ is set to 1.

A transmit process sends a signal through the communication module (channel). However, if more than one node try to transmit its signal, there should be a collision. The signal contains a communication packet to other robot or a collision report for an acknowledgement signal. Figure 3 shows the flow chart for a transmit process.

The transmit process contains three parts. The left part of the flow chart, decides a usage of channel (CD) and transmits a signal if the channel is idle ($CD = 0$). If a channel is valid after a transmission, it means that there is no collision or while there is a collision, a node does not know this. Then, if a $CR - R$ is not received within T_{cn}, ($Receive\_CR - R = 0$), there is no collision and a node finishes a transmit process. However, if there is a collision, a node which transmits second to the last,

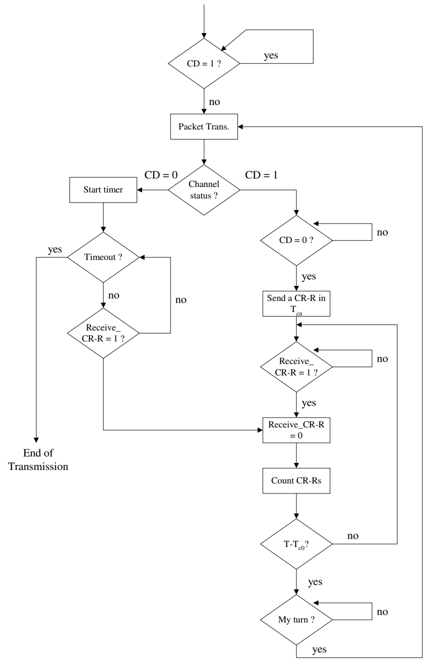

Fig. 3. Flow chart of a transmit process

should send a $CR - R$. Other nodes can receive this $CR - R$ and executes the right part of the flow chart. The right part represents a process invoked after a collision. Each node, n, transmits a $CR - R$ in T_{cn}. The second latest node transmits a $CR - R$ at the moment that CD becomes 0. The latest node, as already explained, does not send a $CR - R$ and receives $CR - R$s from the other nodes.

Each node can decide its order for retransmitting by counting $CR - R$s from the other nodes after transmitting its $CR - R$. If a node receives no $CR - R$ after it sends its $CR - R$ during $T - T_{c0}$, it retransmits first. Then, a node which receives one $CR - R$ retransmits. Thus, all nodes can retransmit its communication packet according to the order of priority after the collision, which was explained in Sec. 2.2.

3. COMPUTER SIMULATIONS

In this section, the simulation results of the two scenarios (a disaster and a saturation) and comparison of them are presented. As assumed before, the channel was slotted with the duration of each timeslot which equals twice of the propagation delay. A fixed packet size was considered and the following parameters were used in computer simulations.

Channel bit rates	38.4kbps (26μs bit time)
Propagation delay, τ	104μs
Slot time	2 τ
Packet size, T	5 slots, 25 slots (5200μs)

First, a relation between a collision node, n and a channel throughput, S in the saturation scenario (after a successful packet transmission by each station, a new packet is immediately generated) was simulated. In a CSMA/CD-R protocol, S is independent of n on higher n than 30. Figure 4 shows the simulation results in the case of $T = 5$. When a small number of nodes collides, a channel throughput in a CSMA/CD protocol is higher than in a CSMA/CD-R. On the other hand, a CSMA/CD-R shows increasingly superior performance to CSMA/CD as the number of collisions increases. Figure 5 shows the simulation results in the case of $T = 25$.

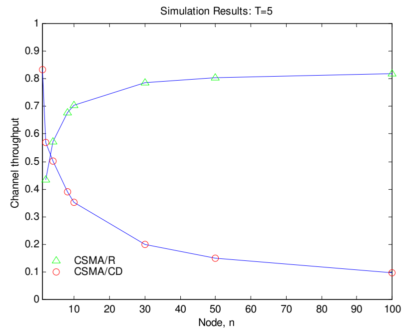

Fig. 4. The comparison of a channel throughput in the saturation scenario ($T = 5$)

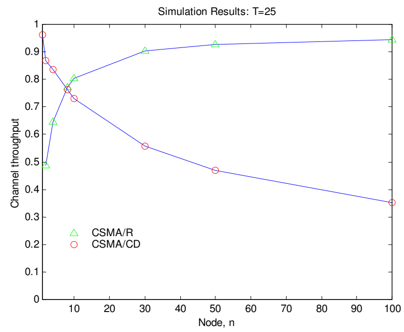

Fig. 5. The comparison of a channel throughput in the saturation scenario ($T = 25$)

In these figures, settling values of CSMA/CD-R were 0.83 when $T = 5$ and 0.96 when $T = 25$. A channel throughput increases with n in the first part.

A relation between a collision node n and a total duration T_D in the disaster scenario (all stations start to transmit at the same time and each station transmits only one packet in the entire process) was simulated. T_D in a CSMA/CD protocol is proportional to a square of n. However, in a CSMA/CD-R protocol, proportional to a n linearly. Figure 6 shows simulation results in the case of $T = 5$. When a small number of nodes collides, the total duration in CSMA/CD is relatively small. However, the total duration increases abruptly as the number of collision increases. On the other hand, CSMA/CD-R is superior to CSMA/CD as the number of collision increases. Thus, CSMA/CD-R has the advantage of scalability over CSMA/CD. Figure 7 shows the simulation results in the case of $T = 25$.

In this section, CSMA/CD and CSMA/CD-R were compared through various simulations. The simulation results show that CSMA/CD-R is superior in the scalability aspect. However, CSMA/CD protocol is more effective in small-size systems. This is due to to the fixed time in CSMA/CD-R, $T - T_{c0}$, during which a node would have to wait its turn by the priority order. Nevertheless, CSMA/CD cannot guarantee the *first-in-first-out* and scalability.

4. EXPERIMENTS WITH CSMA/CD-R PROTOCOL

There are two parts in a robot communication hardware, namely a transceiver (communication) module and a microprocessor. A

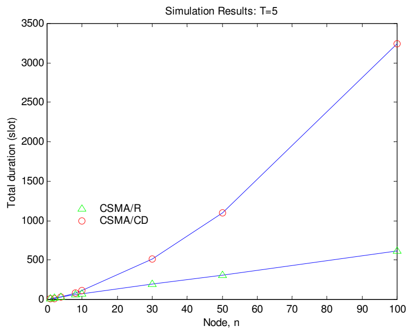

Fig. 6. The comparison of a total duration in the disaster scenario ($T = 5$)

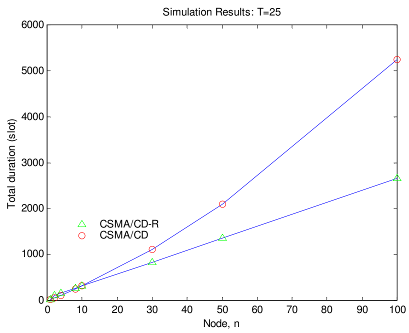

Fig. 7. The comparison of a total duration in the disaster scenario ($T = 25$)

transceiver can transmit or receive a signal. However, it takes some time to switch from a transmit mode or a receive mode and vice versa, i.e., it is half-duplex. It is fixed at a specific frequency. In this paper, a 424MHz frequency module was used.

A microprocessor controls a signal from or to a transceiver module. It is an interface between a higher robot control system and a transceiver, and controls the mode switch of the transceiver. The following signals were controlled by a microprocessor for CSMA/CD-R communication:

- CD (Carrier Frequency Detected): A boolean. If a channel is used, it becomes 1. To check this value, a microprocessor always observes a receiving signal.
- VOC (Validity of Carrier): A boolean. If the received signal is from only one node, VOC becomes 1. If it is from more than a node, it becomes 0. To decide VOC, a microprocessor always observes the received signal and if the signal has a pre-determined protocol, it is assumed to be received from only one node.

Figure 8 shows an overview for a circuit that can transmit or receive a signal, check the signal and switch the mode of a transceiver module. Since the transceiver module is half-duplex, logic 1 is set at the control pin for transmission, and logic 0 for reception. Figure 9 shows a PCB for communication part, implemented on small-size robots (Fig. 10) for experiments with CSMA/CD-R.

Five robots (center of the figure) communicate with each other using 424MHz frequency and another robot (right of the figure) receive the whole signal to show the status of a channel in the computer.

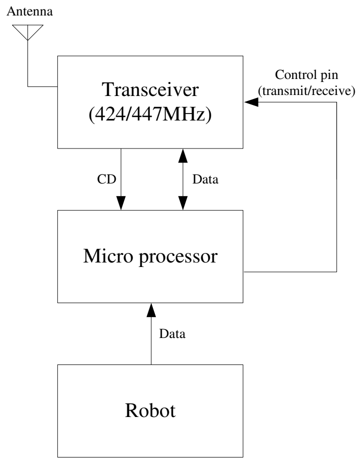

Fig. 8. An overview for a communication circuit

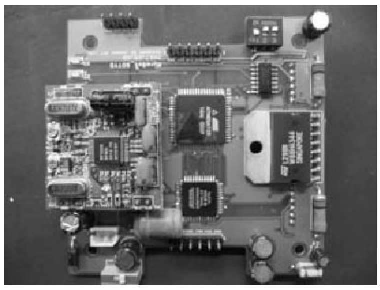

Fig. 9. Implementation of a communication part

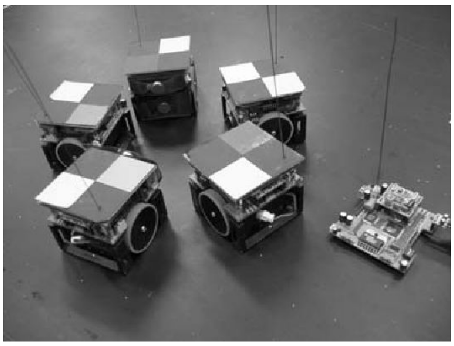

Fig. 10. Five robots communicate by CSMA/CD-R

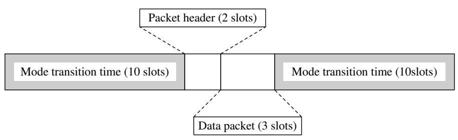

Fig. 11. Data format ($T = 25$)

It takes $2ms$ to change a mode of a commercial communication module, which means 20 slots for transitions (reception to transmission and transmission to reception). Moreover, the packet header of 2 slots (2 bytes) is needed as a packet header for securing the data packet against the possible incoming noise. After that, the data packet of 3 slots (3 bytes) is transmitted as shown in Figure 11.

Figure 12 shows experiment results, which are similar to the numerical analysis and simulation results. However, in real experiments, it took more time for a robot to change its com-

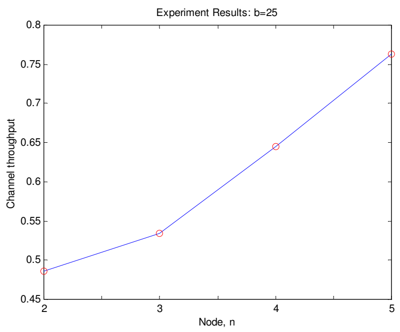

Fig. 12. Communication experiment results ($T = 25$)

munication mode, which accordingly makes poorer results than simulation results.

5. SUMMARY AND CONCLUSION

In this paper, a medium access protocol CSMA/CD-R, designed for wireless networked mobile robots under a distributed robot system was proposed. This CSMA/CD-R communication protocol is suited for a distributed robot system, because there is no external and central device. It means that a robustness, which is a major merit of a distributed robot system, can be maintained. Any robot can use a communication channel at anytime and robots can be added and extracted without any bad influence to a total robot system. After a collision, each robot can retransmit its signal by a priority.

CSMA/CD and CSMA/CD-R were compared through various simulations. Simulation results showed that CSMA/CD-R had a superiority in the scalability aspect.

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