Multi-Channel Utilization for Local Data Sharing in Multi-Layered Wireless Robotic Networks

Rui Teng, Shirayuki Araki, Satoru Shimizu, Kazuto Yano, and Yoshinori Suzuki
Wave Engineering Laboratories, Advanced Telecommunications Research Institute International
Kyoto 619-0288, Japan

***Abstract*—The advances of cloud and edge computing allow networked robots to acquire supporting information anywhere. Meanwhile, cloud and edge computing give rise to a large amount of data information for user to acquire. This leads to a challenging issue for wireless networks because radio resources is limited. To accommodate a number of robots that download map information from wireless LANs (WLANs), it is important for a robotic wireless network (RWN) to improve the efficiency of using wireless resources. The objective of this paper is to investigate how to efficiently use multiple wireless channels for a multi-layered RWN, which employs local data sharing among robots to save wireless resource consumption. Based on the hierarchical structure of multi-layered RWN, we proposed a multi-channel utilization scheme for local data delivery in robot clusters. The joint design of local data sharing via robot clustering and multi-channel utilization increases the available wireless resources for accommodating of the increasing number of service robots. Quantitative analysis results illustrate that the proposed channel separation-and-sharing system increases significantly the capability of robot accommodation and improve the channel availability. Furthermore, the preliminary experiment results confirm the functionality of the proposed system.**

***Index Terms*—Wireless robotic networks, Wireless LAN, map information, wireless resources**

I. Introduction

A robotic wireless network (RWN) involves a variety of service robots, including guidance robots, wheel chairs, and carrier robots [1], [2]. Cloud and edge computing facilitates service robots to obtain advanced information such as navigation map anywhere [3], [4]. The map information is provided by map servers that are distributed cloud or edge servers, and the map information is periodically updated based on the road and environment status. To enable safe movement and location-dependent services, robots need to download map information smoothly from a server through wireless networks. Such wireless networks are based on wireless local area networks (WLANs) or cellular networks, due to their prevailing deployment [5].

To stably acquire map information for mobile robots, high data-throughput in a RWN is necessary when there are a large number of robots. Considering that a shared wireless network may involve users with other applications, a wireless networking system for service robots should cope with the limited wireless resources for accommodating a number of robots [6].

Although advances have been achieved in WLAN and cellular systems, the limited radio resources incurs a constraint for RWN to support a number of service robots [6], [7]. There will be a large consumption of limited wireless resources if all robots communicate with map server through the access point (AP) or base station (BS) of wireless networks. Moreover, RWN especially confronts the constraint of wireless resources with the increasing number of service robots.

This paper investigates a joint approach of multi-channel sharing mechanism and robots clustering, which allows robot to locally share map information acquired through WLANs [6]. Both studies on channel selection and channel sharing have been extensively addressed for WLANs. There are a number of studies on channel selection for a BSS, and channel assignment for multiple BSSs [8]–[10]. Channel sharing has been extensively studied in cognitive radio technologies. Sharing of channel in cognitive radio allows the secondary user to uses a licensed channel only when the primary users do not use the channel [11], [12]. Channel assignments for wireless links in ad hoc networks enable channel reuse and separation [13]. Moreover, the studies on Quality of Experience (QoE) based WLAN resource management and configuration show the effectiveness in improving shared use of wireless resources [14]. On the other hand, to the best of our knowledge, few studies to date have examined in detail about joint utilization of multi-channels and the WLAN based hierarchical structure for local data sharing in RWNs.

In this paper, we propose a multi-channel utilization scheme for hierarchical RWNs. The proposed scheme allows clustered robots to efficiently use multiple channels for local data sharing so as to enable the RWN to accomodate a large number of robots. The basic idea of this study is on the basis of the study of multi-layered RWN, which employs robot clustering to enable local data sharing among robots nearby [6], [15]. With clustering of robots that are near to each other, it is possible to separate wireless channels for the data sharing in a cluster and the data communication with the AP. Both quantitative analysis and real network implementation are carried out to assess the effectiveness and functionality of the proposed system. The analytical results illustrate that the proposed channel separation-and-sharing system increases significantly the capability of robot accommodation and improve the channel availability. The preliminary experiment results confirm the functionalities of the proposed system.

II. System Architecture

A RWN consists of a map server and a number of robots. The map server performs edge computing in constructing, updating and distribution of local navigation map to assist movement safety of robots [1], [3], [4]. Each robot acquires map information from the map server through wireless networks such as WLANs or cellular networks [15].

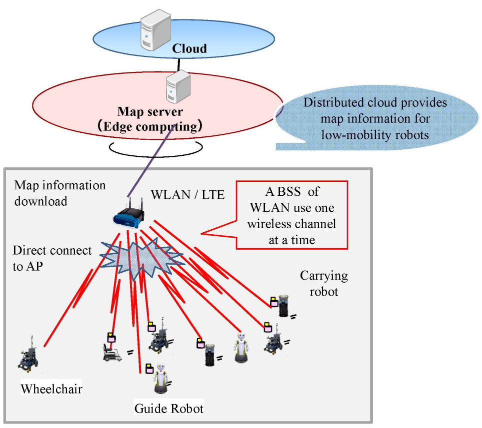


Fig. 1: A Wireless robotic network with downloading of map information directly from the access point or base station.

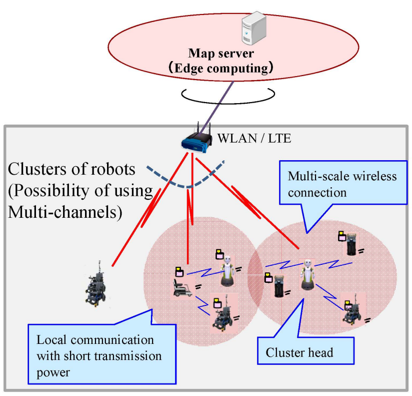


Fig. 2: Multi-layered wireless robotic networks with robot clustering for local data sharing.

A conventional wireless robotic network is shown in Fig. 1, in which each robot directly downloads map information from the map server. To save the consumption of radio resources for a RWN to accommodate the increasing number of robots, we consider hierarchical wireless networks by local clustering of robots [6]. The system model considered in this paper is shown in Fig. 2, in which the hierarchical RWN is constructed by clustering of robots for local data sharing [6], [15].

In a robot cluster, only the cluster head (CH) downloads map information from the server. Other robots (cluster members (CMs)) obtain the map information from the CH with small transmission power. Comparing with that all robots obtain map information directly from the server via communication with the access point (AP) of WLANs, local sharing of map information highly reduces the wireless resource consumption [6], [15]. The scale of a cluster can be restricted by setting a maximum cluster size. Moreover, a CH can also determine the size of a cluster by taking into account the available wireless resource in a cluster.

This paper focuses on the study of the WLAN based RWNs. A cluster based hierarchical RWN provides possibilities of local data sharing and channel separation between the AP and robot clusters. To enable the hierarchical RWNs, three kinds of radio interfaces is employed at each robots [7]. One radio interface allows long-range (global) communication to the AP. Another interface is used for short-range communication and has a small transmission power. The third radio interface is utilized as a control interface, which periodically sends beacons to its nearby neighbors for clustering management. With the advances of wireless communications, multiple RF interfaces are expected to be a low cost for a networked robot.

III. Channel Separation and Multi-Channel Sharing

Clustering of robots provides opportunity of channel separation among robot clusters . Further, using of different channels at AP-CH pairs and CH-CM pairs increases available wireless resources for the network. The object of multi-channel utilization in a RWN is to improve the availability of wireless resource for the increasing number of robots to acquire map information. In a robot cluster, CM obtains map information from the CH by unicast. By utilizing hierarchical RWNs, interferences of wireless communications are alleviated since the local data sharing employs small transmission power at robots.

Figure 3 illustrates the basic components and an overview of the proposed multi-channel management system for local data sharing among robot clusters in RWNs. Channel monitors, which are spectrum sensing devices, are employed to carry out channel monitoring and report periodically the monitoring results to the server. Robots are clustered to enable local communication among robots near to each other [15]. To obtain an appropriate channel in terms of available wireless resources for local sharing of map information, each cluster issues a channel assignment request to the server from its CH. The server selects the best channel for the cluster based on the channel monitoring results, and then assigns a channel to the requesting cluster.

A. Multi-Channel monitoring and measurement

The availability of a channel is calculated from channel occupancy ratio (COR). The COR of a channel is defined as the portion of channel active time to the total time observed. COR status is monitored by channel monitor, which can monitor a broad range of channels involving those in 2.4 GHz band and 5 GHz band. Channel monitors are placed inside a RWN. For the case that there are multiple channel monitors, the corresponding monitor for a robot is the one nearest to the robot.

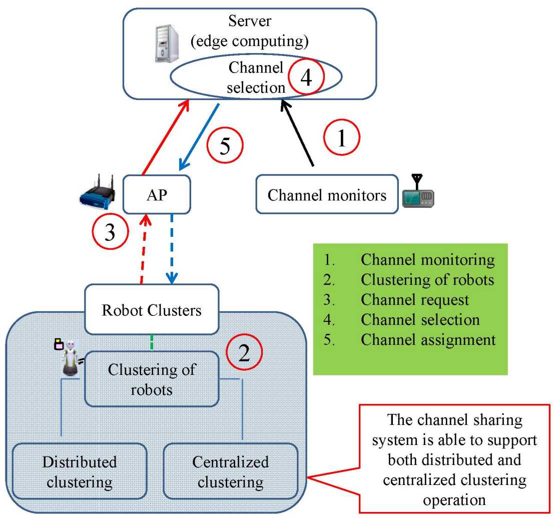


Fig. 3: Channel request and assignment System.

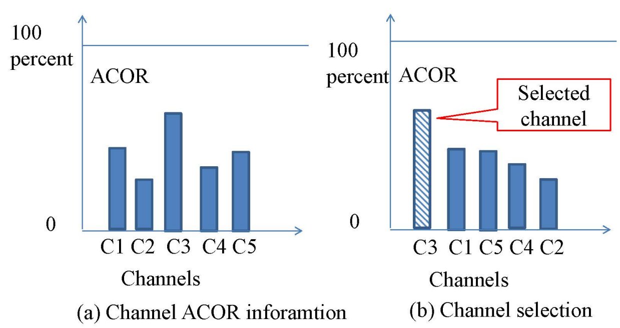


Fig. 4: An example of channel selection.

B. Channel selection scheme

1) Basic scheme: When a robot becomes a CH, it issues a channel selection request to the server, which selects and assigns a channel to the CH. Moreover, when the COR of the channel consumed in a cluster is larger than a threshold, the CH in a cluster will also issue a request of channel assignment.

Channel selection is carried out at the server based on the monitoring results of each channel. The server computes available radio resource (ARR) as $ARR = 1 - COR$. Ranking is carried out among channels being monitored by a monitor, as shown in in Fig. 4. On receiving a channel selection request from a CH, the highest ARR, meaning the best channel, is assigned to a channel-requesting cluster. In case there are multiple channels that have the same best ARR, these channels will be ranked with order of frequency, for example from low to high, for a cluster to choose.

The ARR based channel selection and assignment lead to the multi-channel sharing among robots, as illustrated in Fig. 5

2) Selection-collision avoidance: To avoid the multiple clusters selecting the same channel at the same time, a mechanism of channel selection avoidance is employed in the channel selection mechanism. On receiving a channel assignment request, the server assigns a channel to the requesting cluster

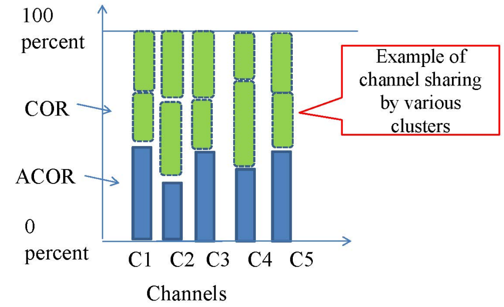


Fig. 5: Channel sharing effect.

sequentially when there are multiple requests arrive in a short time. We say that channel collision occurs when the server assigns the same channel that is best in the channel ranking that confronts an insufficient update of channel information in a short time. To avoid channel selection collision, the server set up a preserved COR consumption on a channel when the channel is assigned to a cluster. The amount of preserved COR consumption can be manually predefined, or based on the average COR consumption per cluster by allowing each CH reports its COR consumption amount on average in a period to the server.

IV. Quantitative Evaluation

A. The capacity of network accommodation of robots

We define robot-accommodation capacity as the maximum number of robots that can be supported in RWNs. We quantify the accommodation capacities of the conventional approach using non-layered communication and the proposal approach using layered communication and dynamic channel selection.

Given a set of wireless channels C_{set} with n candidate channels for robots to use. Let $DataSize$ be the average size of the map data that a robot downloads from the sever per second. Let the average throughput for a robot on a channel be denoted by Thp_{ap}. The number of robots that can be accommodated in a single channel is $Ac_{conventional} = \frac{Thp_{ap}}{DataSize}$.

Meanwhile, the accommodation capacity of the proposed system with channel separation is analyzed based on two cases in terms of the number of available channels.

Case1: There are a sufficient number of channels for each cluster to have a different channel. Suppose that the CH downloads the map information that is same with that to be distributed to the clients. Let each channel have an average $thp_{cluster}$. Then the max number of accommodation capacity of a cluster is $Ac_{cluster} = \frac{thp_{cluster}}{DataSize}$. The robot accommodation capacity of the network can be expressed as

$$Ac_{Proposed} = \frac{Thp_{ap}}{DataSize} \times Ac_{cluster}. \quad (1)$$

We can see that the clustering based channel separation enables the network to accommodate $Ac_{cluster}$ times the number of robots.

Case2: There is a limited number of channels, some clusters employ the same channel .

Proposition 1. *Compared with conventional non-layered communication in a WLAN, the proposed approach enables an increased number of* $\frac{Thp_{cluster} \times k}{DataSize}$.

Proof. Let the number of channels, not including the channel for AP using, for clusters to use be k. The robot accommodation capacity of the network for this case can be expressed as

$$Ac_{Proposed} = \frac{Thp_{ap}}{DataSize} + \frac{Thp_{cluster} \times k}{DataSize}. \quad (2)$$

Note that the number of robots that can be accommodated in single cannel BSS is $Ac_{conventional} = \frac{Thp_{ap}}{DataSize}$.

Consequently, the proposed approach enables an increased number of $\frac{Thp_{cluster} \times k}{DataSize}$.

□

B. Measurement of channel-sharing effectiveness

We measure the effectiveness of channel sharing by the availability of wireless resource for accommodating robots. The availability of a channel resource (in terms of ARR in this paper) is defined as whether or not enough resource is available for robot to operate the map service. A good sharing scheme can accommodate a large number of robots.

A basic analytical model of channel sharing is shown in Fig. 6. Let the number of robot clusters be N. Let the number channels for robot clusters to use be K. For simple analysis, we assume $K = 2$. This set up refers to the channel environment of 2.4 GHz based WLAN, where there are mainly three separated channels. We consider one is for AP use, another two channels are shared by robot clusters. Suppose that the average COR consumed by each cluster is C and the maximum number of robot be accommodated in a channel is M, which is the lower bound integer of $1/C$. We try to derive the performance difference between the proposed channels sharing approach with the random channel sharing approach, which is chosen because it is a basic approach that does not rely on priori knowledge of wireless communication conditions and has been employed as a basic method in multi-channel assignment [13].

According to the correlation of N with the M and K, three cases are classified to quantify the probability of channel availability.

For the case that $N > (M \times K)$, the probability of channel availability is 0, meaning that there are robot clusters that will not be accommodated in the network.

For the case that $N \leq M$, the probability of channel availability is 1, meaning that all robot clusters can be accommodated in the network.

For the case of $(K \times M) \geq N > M$, We derive the probability of channel availability as follows. At first, the probability of channel availability with respect to random channel selection can be expressed as

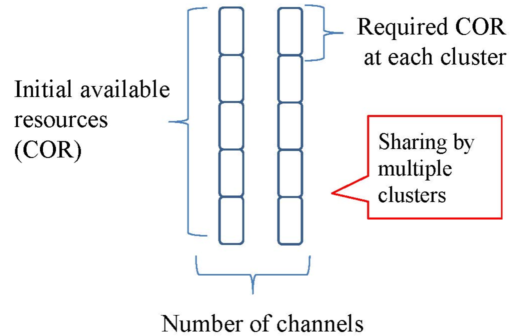


Fig. 6: Analytical model.

$$P_{random} = \frac{\sum_{i=N-M}^{M} \binom{N}{i}}{2^N}. \quad (3)$$

Second, the probability of channel availability with respect to proposed channel selection for given information of M can be expressed as

$$P_{proposed} = 1. \quad (4)$$

Hence, the ratio of probability of channel availability to the random channel selection can be expressed as

$$Ration_{availability} = \frac{P_{Proposed}}{P_{random}} = \frac{2^N}{\sum_{i=N-M}^{M} \binom{N}{i}}. \quad (5)$$

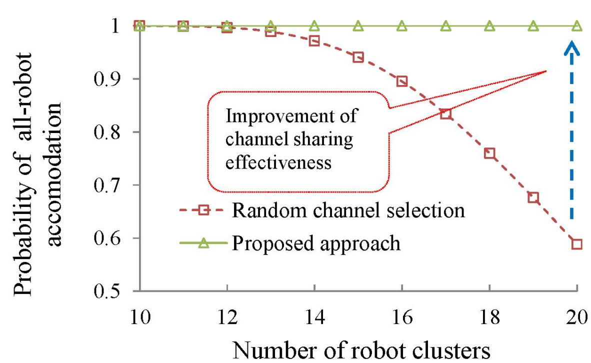


Fig. 7: Probability of accommodation of all robots by channel sharing. (K=2, and M=10)

Figure. 7 illustrates the probability of accommodating all robots for the case $(K \times M) \geq N > M$ and there are two channels, each of which can accommodate a maximum of 10 robots. It can be seen that the larger number of robot clusters the relative larger probability for the proposed approach to accommodate all robots in the network, comparing with the random selection approach.

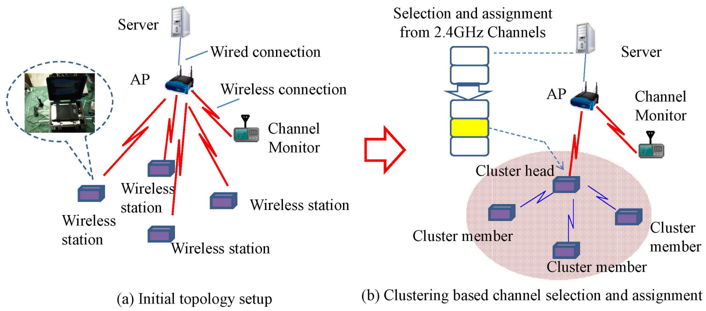


Fig. 8: Experiment setup.

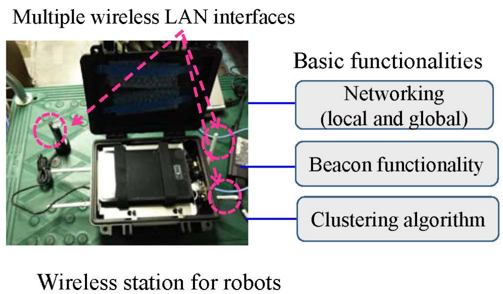
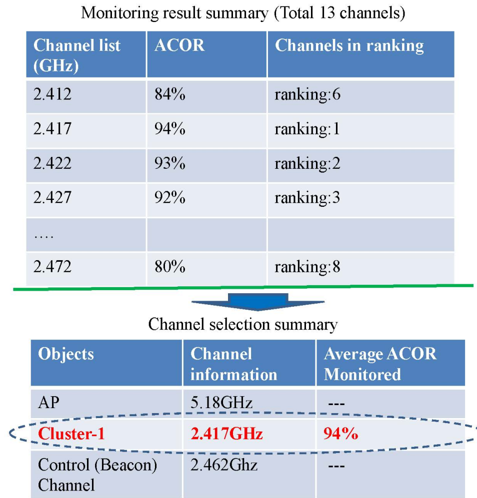


Fig. 9: A wireless station.

V. Preliminary results of implementation based experiment

The basic system of clustering-based channel management is implemented on the real RWNs based on WLANs. The implementation involves robot clustering operation, channel monitoring, and channel request, selection and assignment. An preliminary experiment is conducted to verify the basic system functionalities for a one-cluster RWN (The multiple-cluster RWN is not taken into account in the experiment at this stage.) . The layout of the experimental network is shown in Fig. 8. The network consists of a server, an WLAN AP, a channel monitor and four wireless stations for robots. Since this experiment focuses on examining the basic channel selection function for one robot cluster, the experimental devices are deployed near to each other within a few meters. There are no special interference sources being set up in the experiment. A wireless station employs multiple radio interfaces hence to enable global communication with the AP, local communication among robots and beacon function for clustering control, as illustrated in Fig. 9. The AP and control beacons utilize a pre-determined 5 GHz channel and a 2.4 GHz channel, respectively. The channel monitoring and channel selection for wireless station clusters are carried out among the 13 channels of 2.4 GHz WLANs.

In the experiment, the four wireless stations form into one cluster. The results of channel monitoring and the results of channel selection is shown in Fig. 10. The second channel at frequency 2.417 GHz has the largest ARR, and is selected as the channel for the cluster of wireless stations. From the experiment, we verify the operations associated with the functionalities of channel monitoring, channel separation for AP and a robot cluster, and clustering based channel request,selection and assignment.



Monitoring result summary (Total 13 channels)

Channel list (GHz)	ACOR	Channels in ranking
2.412	84%	ranking:6
2.417	94%	ranking:1
2.422	93%	ranking:2
2.427	92%	ranking:3
....		
2.472	80%	ranking:8

Channel selection summary

Objects	Channel information	Average ACOR Monitored
AP	5.18GHz	---
Cluster-1	2.417GHz	94%
Control (Beacon) Channel	2.462Ghz	---

Fig. 10: Experiment results.

VI. Conclusion and future work

This paper introduces a method of exploring multiple channels in a WLAN based multi-layered RWN for robots to download map information. Clustering based channel separation, selection are proposed to enlarge the limited wireless resources of WLANs for robots. The analytical results reveal that the proposed approach significantly increases the robot-accommodation capability and the channel sharing effectiveness. The experiment results verify the functionalities of the proposed system for multiple channel selection and sharing in RWNs. Future research includes extensive evaluation of the proposed approach, experiments on channel assignment for multiple cluster scenarios, and examining diverse application cases of RWNs.

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