Efficient Acquisition of Map Information for Service Robots using Local Data Sharing over Multi-Layered Wireless Network

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Abstract:
This letter aims to address the problem of wireless resource constraints in wireless robotic networks to enable stable acquisition of map information for a number of robots. In order to reduce wireless resource consumption, we propose a two-step data acquisition scheme for robots. In the proposed scheme, only a few robots directly download map information from the server, most robots acquire map information by means of local data sharing with short range communications among nearby robots. A distributed clustering scheme is utilized to decide which nodes download map information from the server. Evaluation results show that the proposed scheme highly reduces wireless resource consumption, especially when there are many service robots.

Keywords: Robotic wireless network, wireless resource efficiency

Classification: Wireless communication technologies

References

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*(The contents of this manuscript have been partly presented in [3] and [4].)
1 Introduction

A robotic wireless network consists of a map server and a number of robots, which are connected via a wireless network such as wireless local area networks (WLANs) or Long Term Evolution (LTE) [1, 2]. Fig. 1(a) illustrates the conventional wireless robotic network, in which each robot downloads map information directly from the map server. Increasing number of service robots causes large interference among robots and heavy load on the access point (AP) or base station (BS). This in turn leads to possible failures of stable acquisition of map information for robots.

To overcome this problem, this letter proposes a two-step acquisition of the map information. At first, some of robots directly download the map information from the server. Next, the downloaded map information is shared among robots within the area where the downloaded information is valid. By sharing information with a small transmission power, interference range is reduced, and spectral reuse is enabled. The detail system structure and how to determine the robot downloading the map information and the range of information sharing, i.e. how to make a cluster for local data sharing, are introduced in the next section. Different with the scheme proposed in reference [2], this letter proposed a distributed, simple, and fast clustering scheme that achieves similar effectiveness in saving the consumption of wireless resources.

2 Two-Step Acquisition of Map Information with Wireless Resource Efficiency

2.1 System Structure

As shown in Fig. 1(b), the key idea of the proposed system is that two-step acquisition of map information is carried out among robots. At first, only a part of robots in a robotic network need to download map information from the server. Then, in the second step, other robots obtain the map information from a nearby cluster head using a low transmission power. This leads to efficient spatial reuse of wireless resource and increase the number of accommodate robots.

In the proposed system, three kinds of radio interfaces are employed at each robot[2], as illustrated in Fig. 1(c) that shows a practical WLAN-based wireless node for the robotic wireless network. One radio interface supports long-range communication to the AP or BS, provided with a large transmission power for a wide coverage. Another interface is for short-range communication to locally share data among nearby robots, and it has a low transmission power to cover only nearby robots. The third radio interface is used as a control interface, which periodically sends beacon signals to its nearby neighbors. Such periodic beacons allow a robot to detect its neighbors and form clusters among nodes for local communications. For easy reconfiguring of cluster and distributing control messages among robots, we suppose to use independent basic service set (IBSS) of WLAN for the second and third radios.
2.2 Distributed clustering of robots

In the proposed robotic wireless system, a distributed-and-paralleled clustering scheme is utilized to determine which node should download the map information and which nodes should share the map information. Compared with the scheme proposed in reference [2] that utilizes multiple phases of clustering for local optimization, the proposed scheme is simple, fast for clustering, and does not require strict synchronization among robots. In the distributed clustering procedure, each robot carries out the cluster formation process periodically. The basic cluster formation process at a stand-alone robot X that does not belong to any cluster is described as follows. 1) Robot X becomes a cluster head at a probability P; 2) if X becomes a cluster head, it issues cluster head announcements to its neighbors using the radio for sending beacons; 3) if X, which does not become a cluster head, receives a message of cluster head announcement from its local neighbor node, it then joins the cluster and becomes a client of the cluster.
2.3 Prioritized clustering scheme
We further propose an advanced clustering scheme that controls the cluster head generation in a distributed manner. Each candidate of robot has a probability $\text{Prob}_{CH}$. $\text{Prob}_{CH}$ is designed to be proportional to the number of local neighbours. This is enabled by prioritized generation of cluster-head announcement time. The control algorithm is as follows. Let $\text{Nei}[X]$ denote the number of local neighbours of a robot $X$. Given a time pool $P_a[x]$ for a robot to issue the cluster head announcement in each clustering period. The maximum $P_a[x]$ is set to $S$ slot units, where $S$ can be an integer multiple of the number of robots in the network. The announcement time $T[x]$ at each robot is randomly generated in $P_a[X]$. By allowing $P_a[X] = S - \text{Nei}[X]$, the robot $X$ with more number of local neighbours has a higher probability to issue a announcement of cluster head than that with less number of local neighbours. An example is shown in Fig. 1(d), in which robot A has a higher probability of being a cluster head than others. To synchronize the start time of clustering, AP periodically issues clustering formation message that triggers the cluster formation each time.

3 Simulation evaluation
To validate the effectiveness of the proposed approach on reducing wireless resource consumption, computer simulation is conducted. We compare the performance of the proposed schemes and with the conventional scheme that uses WLAN to directly download map information from the server. Furthermore, we also investigate the performance difference between the proposed schemes and the local optimized clustering scheme proposed in [2]. The simulation parameter setup is shown in Table I. The basic setup of network environment is shown in Fig. 2(a). We assume that the path loss exponent is 3, supposing the possible building environment. The transmission powers of long-range and short-range communication are set to 14.1 dBm and $-3.98$ dBm, respectively. Since this letter focuses on the basic features of constructing map-sharing clusters, the movement of robot nodes is not taken into account in the evaluation.

In the evaluation, we measure the wireless resource consumption by

$$\text{WirelessResource} = \text{BW} \ast \text{OccuTime} \ast \text{InterferenceArea},$$

with a unit of MHz·second·m$^2$. In this expression, BW stands for the channel bandwidth. Channel occupancy time (OccuTime) is the minimum time that the transmission channel is used to transmit the object map data to a robot. In the simulation, OccuTime is calculated by $(\text{Map data size}/\text{Data rate})$ in order to reflect the fundamental time factor to transmit the map data to a robot. The interference area of a robot refers to the size of the area in which the received power is greater than $-82$ dBm. To explicitly represent the impact of the multi-layered wireless structure on wireless resource consumption, we assume that each robot is able to obtain map information in a separated time regarding to other robot, ignoring the contention effect of channel access among robots.
Table I: Simulation Setup.

| Parameters                        | Setup                                      |
|-----------------------------------|-------------------------------------------|
| Number of Robots                  | 5–50                                      |
| Network area                      | 40 m $\times$ 40 m square                 |
| Positions of robots               | Random with uniform distribution          |
| Number of robot topology settings | 100 (each is static)                      |
| Position of the AP                | (20, 20)                                  |
| Data size of map information      | 2 Mbits                                   |
| Bandwidth                         | 20 MHz                                    |
| Data rate                         | Adaptive (referring to IEEE 802.11g WLAN)[5] |
| Path loss exponent                | 3                                         |
| Transmission power (long range radio) | 14.1 dBm                               |
| Transmission power (short range radio) | $-3.98$ dBm                             |

Clustering results are shown in Fig. 2(b). For the basic distributed clustering scheme that does not employed prioritized selection of cluster head, the ratio of client number to the total number of robots increases from above 28 percent to 79 percent as the total number of robots increases from 5 to 50. The result verifies the effectiveness of data sharing cluster that requires only a small number of robots to be cluster heads for global data communication with the AP in a WLAN. The reason of this result is that the increase of robots causes the increase of the local neighboring robots, leading to more candidate clients of a cluster head. Moreover, the prioritized scheme increases the client ratio by 2.7 percent in average compared with the basic distributed cluster scheme. The reason of this result is that the prioritized clustering scheme allows a robots with more local connected robots to be a cluster head with a higher probability.

Fig. 2(c) shows the results of wireless resource consumption relative to the conventional scheme in downloading map information. The basic distributed clustering scheme results in a significant reduction of wireless resource consumption, compared with conventional scheme that directly downloads the map information from the server. Wireless resource consumption is reduced by 24 percent for the network with 5 robots, and the reduction grows to 71 percent when the number of robots is 50. These results are mainly attributed to the small interference area in data acquisition among robots by using the local communication between client nodes and their cluster head. The prioritized scheme further saves 4.4 percent wireless resource consumption in average compared with the basic distributed cluster scheme. The degradation in wireless resource consumption for the basic clustering scheme, relative to the local optimized scheme, is reduced by 47 percent when utilizing the prioritized scheme.

Meanwhile, local optimized scheme may require multiple rounds of clustering process that attempt to allow each robot to join in an appropriative cluster [2]. As shown in Fig. 2(d), the basic distributed scheme and the prioritized scheme requires only one round of clustering process to allow each robot to finish its clustering process, and local optimized scheme requires up to 1.5 rounds of clustering process in average when the number of robots is
Fig. 2: Simulation results.

large.

4 Conclusion

This letter studied the efficient use of the limited wireless resources for wireless robotic networks. Reducing wireless resource consumption is significant for a number of service robots to enable stable acquisition of map information. We proposed a robotic wireless system that employs two-step acquisition of map information in order to cope with the wireless resource constraints for a number of service robots. In the proposed wireless system, robots are coordinated by means of distributed clustering in an autonomous manner to download and locally share map information. The locally sharing of map information in each cluster with short-range communication leads to wireless resource reuse and the saving of area-spectral consumption of wireless resources. Evaluation results reveal that the proposed scheme achieves significant reduction of resource consumption especially when there are a large number of robots in a network.

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