Effects of Wireless Signal Attenuation on Robot Team Performance

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Abstract

This work investigates how wireless signal attenuation affects a team of mobile robots performing exploration. Many coverage tasks, such as search and rescue or exploration, can be performed more effectively when robots communicate with one other. However, in real world environments, maintaining communication can be difficult due to unpredictable wireless signal propagation. In this paper, we investigate the wireless network connectivity in an outdoor area that consist of concrete wall and pillars. Preliminary simulation and physical experimental results are compared to demonstrate the effects of signal attenuation on robot team performance.

Introduction

In order for autonomous mobile robot systems to successfully perform missions that are too difficult or dangerous for humans, they must be able to effectively cooperate and coordinate their actions as a team. Robot team efficacy can be increased through communication by speeding up completion, preventing robots from interfering with one another, and reducing duplication of work. Unfortunately, in many real world applications, the wireless signal can be weak or absent. Communication performance is affected by limited bandwidth, environmental interference (e.g. walls), and degrades as the distance between robots increases.

In the wireless networking community, researchers have demonstrated that man-made structures such as concrete and steel walls interfere with communication transmissions (Seidel and Rappaport 1992). Signal strength through walls suffer greater loss than those in open or free space. Reflection and diffraction from glass windows can also interfere with signal propagation. Propagation prediction is site-specific and depends highly on building structures and environmental conditions.

In the robotic community, researchers acknowledge that unreliable communications can affect robot team performance. To overcome this limitation, researchers propose methods of cooperation that do not rely upon digital messaging. For instance, approaches inspired from animals include: ant or swarm robots (Koenig, Szymanski, and Liu 2001) where robots leave virtual pheromones or trail markings in the environment to direct robot behaviour and potential fields (Howard, Mataric, and Sukhatme 2002) in which robots are attracted to the goal and repulsed from obstacles and other robots.

Others have considered reducing the amount of messages transferred from robot to robot. Researchers that have considered direct communications with network constraints include: (Arkin and Diaz 2002) in which robots are required to maintain line-of-sight with other robots, (Meier, Stachniss, and Burgard 2005) in which message size is reduced by allowing robots to communicate polygonal representations of the map, and (Roy and Dudek 2001) where rendezvous approaches allow robots to meet up to exchange information about the environment.

Although researchers are aware that unreliable communications can affect robot team performance, often times multirobot cooperation approaches are only performed in simulation (Dawson, Wellman, and Anderson 2010). Robotic simulators can quickly validate coordination algorithms without acquiring expensive robotic equipment. However, in robotic simulators, wireless communication networks are not modelled well. It is one reason why there are discrepancies between results of simulated and physical experiments.

In this paper, we investigate the wireless signal attenuation in a physical environment and examine how it affects a team of robots in exploration. The environment is an outdoor campus area consisting of man-made concrete pillars and tall glass windows. Simulation and physical experimental results will be compared to demonstrate the effects of wireless path loss.

In the next sections, a brief literature review of cooperation and communication in multirobot systems is presented. It will include related work on wireless signal propagation issues and the effect of communication on robot team performance. Next, the Approach section discusses the robot team's task, algorithm, communication mechanism, and wireless communications network metrics. Following, the Experiment section presents the experimental setup and the results from simulation and physical robot experiments. Finally, there is a discussion on how artificial intelligence methods can be used in simulators to enhance prediction of multirobot system performance in real world environments that are noisy, dynamic, or unpredictable.

Cooperation in Multirobot Systems

Definitions of multirobot cooperation vary but typically focus on the task, or method of cooperation, that increases system performance. (Matarić 1995) describes cooperation as "a form of interaction, usually based on some form of communication".

Implicit and Explicit Cooperation

Cooperation is characterized as implicit or explicit. With implicit cooperation, task agreement is not chosen beforehand or conveyed between robots. Rather, a robot relies on its perception of the world and its observation of other teammates' actions. With explicit cooperation, goals and actions are directly communicated from robot to robot. State variables used to calculate self utility and the other robots' utilities are communicated so that robots are explicitly aware of other teammates' goal and actions.

Centralized Control

Under centralized communications architectures, a single computer or robot acts as the leader. Robots communicate with the leader and the leader is responsible for making the decisions to coordinate the team. Examples of centralized approaches for multirobot exploration include (Simmons et al. 2000).

The advantage of a centralized approach is that there can be optimal planning since one computer coordinates the entire team. However, each team member is required to remain in communication range with the leader so that the leader has the latest information to coordinate the team in which can require a high bandwidth. Therefore, in an unknown or dynamic environment with a large number of robots and limited communications, a centralized approach may not be suitable. In addition, performance of the team relies heavily on the leader. If the leader fails and a new leader is not chosen then the entire team becomes ineffective. Therefore, centralized approaches are more appropriate for teams of small sizes in a static environment with global communications (Dias and Stentz 2003).

Decentralized Control

In decentralized approaches, robots act independently and use their sensing abilities to make decisions. Although robots can communicate to improve coordination, results are often sub-optimal since planning is local. However, a decentralized approach does not have many of the disadvantages of a centralized approach such as a single point of failure. Researchers have concluded that decentralized approaches have several advantages over centralized approaches (Arkin 1992). For example, in a task in which robots need to spread out such as in exploration, a decentralized approach does not require robots to remain in communication range with a leader.

Several decentralized approaches for coordinating multirobot systems make use of explicit communications. (Yamauchi 1998) present a frontier-based coverage algorithm. Robots detect frontiers, or regions on the boundaries between unexplored and open space, and then expand area knowledge by recursively exploring the nearest unvisited frontier. Robots cooperate by communicating state updates, reducing duplicate coverage by the team.

Communication in Multirobot Systems

Communication in multirobot systems has been categorized using different methods. (Iocchi, Nardi, and Salerno 2001) use the terms direct and indirect communication, which direct communication is described as using some hardware onboard dedicated to sending signals that team members can understand, whereas indirect communication make use of stigmergy (Beckers, Holland, and Deneubourg 1994). (Dudek et al. 1996) provide a taxonomic organization of communication by range, topology, and bandwidth. Communication range is the maximum distance between two robots in which communication can occur. Communication topology describes the hierarchy at which robots can communicate with other robots. Communication bandwidth is the amount of information that can be transmitted from robot to robot.

(Cao, Fukunaga, and Kahng 1997) characterize robot interaction via environment, sensing, and communications. In interaction via environment, there is no interaction between robots but the environment is the communication medium. Interaction via sensing occurs when robots sense (i.e. through vision or RFID) one another without explicitly communicating. With interactions via communication, there is explicit communication with intentional messaging between robots. (Balch and Arkin 1994) describe communications as explicit, the deliberate act of signaling between robots, and implicit, the observations of environment and other robots.

Propagation Issues in Wireless Communications

There has been much research on the propagation issues for wireless networking. In (Eckhardt and Steenkiste 1996), the effects of distance, obstacles, and interference on wireless signals for a 2 Mb/s wireless LAN are investigated. Results suggest that interference makes a bigger difference in error or loss rate than distance. (Jadhavar and Sontakke 2012) propose a propagation model that predicts the effect of environmental configurations on wireless communication reliability. Attenuation factors were measured to find path loss for free space and space with obstacles. The attenuation factor for concrete walls accounted for an additional path loss at 4.86 dB when compared to free space and hardboard which accounted for an additional 2.45 dB. (Seidel and Rappaport 1992) present a prediction model for indoor wireless communications. The model predicts the effects of walls, office partitions, floors, and building layout on path loss. Same-floor and multi-floored measurements were gathered as well as the attenuation factors for cloth-partitioned and concrete environments.

Effects of Communication on Robot Team Performance

A limited number of researchers have demonstrated and presented results on the effects of communication on real robot team performance. (Balch and Arkin 1994) researched how communication affects multirobot systems performance during the tasks of forage, consume, and graze. The impact of different types of communications is compared and includes both no communications and direct communication. Results suggest that communications appears to be unnecessary in tasks in which implicit communications exists and the more complex communications had little or no benefit over basic communications for these tasks.

(Rybski et al. 2001) demonstrate how low bandwidth communication channels affect the performance of a robot team on a surveillance task. Miniature scout robots were required to use very low capacity RF communication systems due to their size. Relying on off-board processing, the robots shared bandwidth. Results suggest that the performance of the system degraded with the increase of communications load.

(Wellman et al. 2011) suggest as robots exchange large amounts of information, they run into the risk of receiving incomplete information due to CPU overload from individual message processing. Specifically, in outdoor areas, maps can become large and as robots communicate map information the network can quickly become saturated. As message loads increase, team performance degrades (Dawson, Wellman, and Anderson 2010).

This research differs because network connectivity metrics and robot team performance are examined for a multirobot systems performing exploration in an environment with concrete walls and weakened wireless signal strengths.

Approach

In this work, the task of the robot team is exploration of an large unknown area. The objective of the exploration task is for a team of robots to cooperatively explore the environment and to map all the unknown and obstacle area as fast as possible.

Exploration Algorithm

Each robot performs frontier-based exploration algorithm (Yamauchi 1998). Frontier-based exploration involves robots recursively exploring an unknown environment while building a map represented by an occupancy grid. Robots use a distance sensor to detect areas that are open, occupied, unknown, or a frontier. Frontier areas are the borders between open and unknown space. Robots explore frontier areas to expand their knowledge of the environment. As an asynchronous approach, robots select frontier areas based on individual utility allowing fault tolerance against individuals being disabled or out of range.

Communications Network Performance Metrics

As robots explore, there only share map information about open area. For the real robots, control commands and communication messages are transmitted over a standard wireless IEEE802.11b network using at 2.4 Ghz wireless router.

The following performance metrics were gathered during the experiments at the physical environment to evaluate the connectivity between the robots and the control machine.

Signal Strength is the quality of the connection between the receiver and access point. Capturing the signal strengths at different points in the environment assists in identifying signal attenuation. Attenuation is the amount of power that a signal loses between the transmitter and the receiver measured in decibels. The path loss depends on the distance between the robots, the number of obstacles between them, and the properties (such as material or density) of the obstacles between them. Signal Strength was captured using the Linux wireless interface tool, iwconfig.

Packet Loss percentage of data packets dropped due to communications network difficulties. It was measured using the network protocol analyzer, WireShark (Combs and others 2007).

Round Trip Time is the amount of time for a packet to be sent to a destination and back again. It was also measured using the network protocol analyzer, WireShark.

Experiments

We hypothesize that wireless signal attenuation effects robot team performance. In order to test this hypothesis, simulation results will be compared to physical experimental results. Robots performed exploration while communicating map information. Simulations and experiments were conducted using two autonomous mobile robots. It is expected that the robot team from simulation will have a better performance than the real robot experiments due to path loss.

Experimental Setup

The robots used were Adept Amigobots®featured with eight sonar sensors. The controller was written using MobileRobots Advanced Robot Interface for Applications (ARIA) 20, a C++ library SDK for MobileRobots platforms, on a Quad Core 3.2 GHz machine running Linux with 6GB of RAM. Robots communicated using a standard wireless IEEE802.11b network over a 2.4 Ghz wireless router. The same code was used for both simulations and real world experiments. Three trials were conducted for each approach. Each trial ran for 10 minutes.

The environment that the experiments were conducted was 15x18 meters consisting of thick concrete walls with both line-of-sight and non-line-of-sight signal propagation between robots (Figure 1). The simulated environment was created to represent the real environment using the same measurements (Figure 2).

Experimental Results

In terms of network connectivity, signal strength, round trip time, and packet loss were captured from the real environment. Figure 3 illustrates the signal strength for the real environment. As shown, the signal strength is lower farther away from the wireless router. It is the lowest behind the concrete pillars since the there is not a clear path to the wireless router.

Figures 4 and 5 illustrates the round trip times for one of the trials from simulation and physical experiments. In simulation, the round trip time did not reach over 0.03 ms.

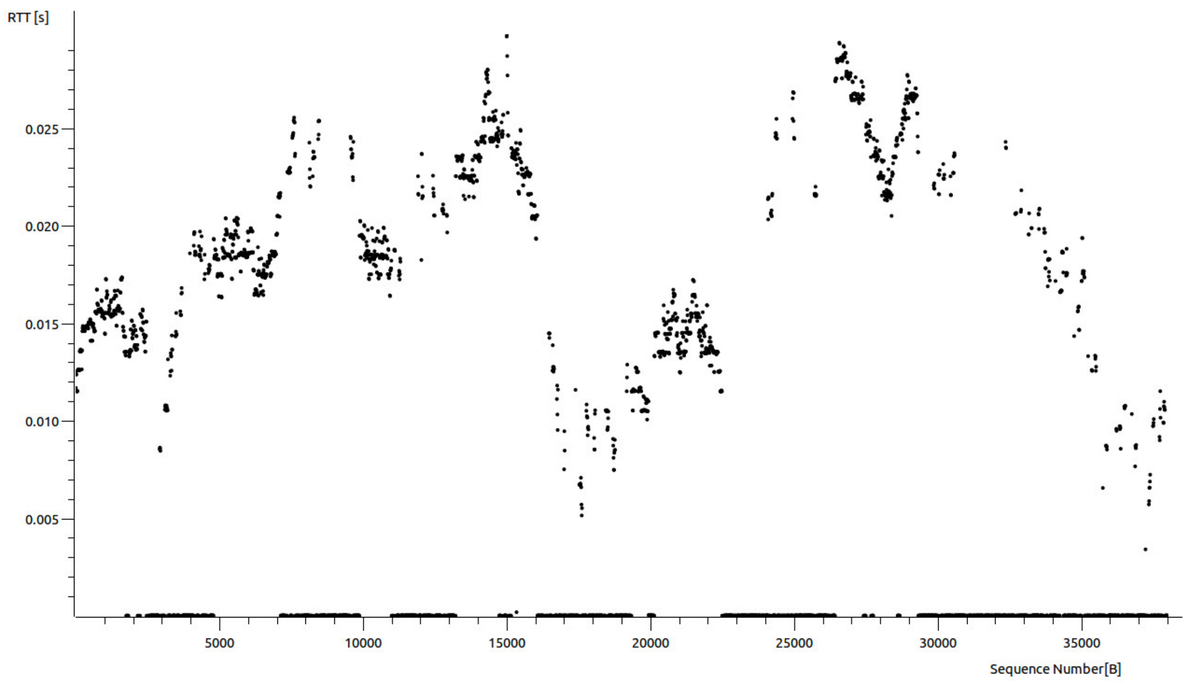

Figure 4: In simulation, the round trip times were 0.03 ms or less.

Figure 1: The physical environment is 15x18 meters. It is outdoors and made of concrete walls and pillars. Experiments were conducted to demonstrate the effects of wireless signal propagation. A 2.4 Ghz wireless router was placed in the environment for communications.

The round trip time for the real environment reached up to two seconds. The average packet loss was 0% for simulation and 3% for the physical environment.

Team performance was captured by gathering total robot coverage of the area. Each robots location and sensor information were used to determine robot coverage. Figures 6 and 7 show the coverage in simulation and physical robot experiments; respectively. In the physical experiment, there was less area coverage and more duplication of work when compared to simulations.

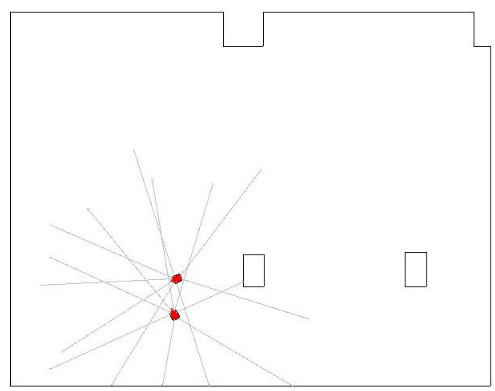

Figure 2: The simulation environment was created after measuring the real environment

Discussion

In this paper, we demonstrated the effects of wireless signal attenuation on physical multirobot systems performance. Compared to simulation, physical experimental results suggest robots complete exploration slower, with more disruptions in wireless network connectivity. In the real environment, the attenuation (path loss) rates and round trip times degraded as the robot moved father away or behind concrete walls and pillars.

There is still much work to be done regarding the ef-

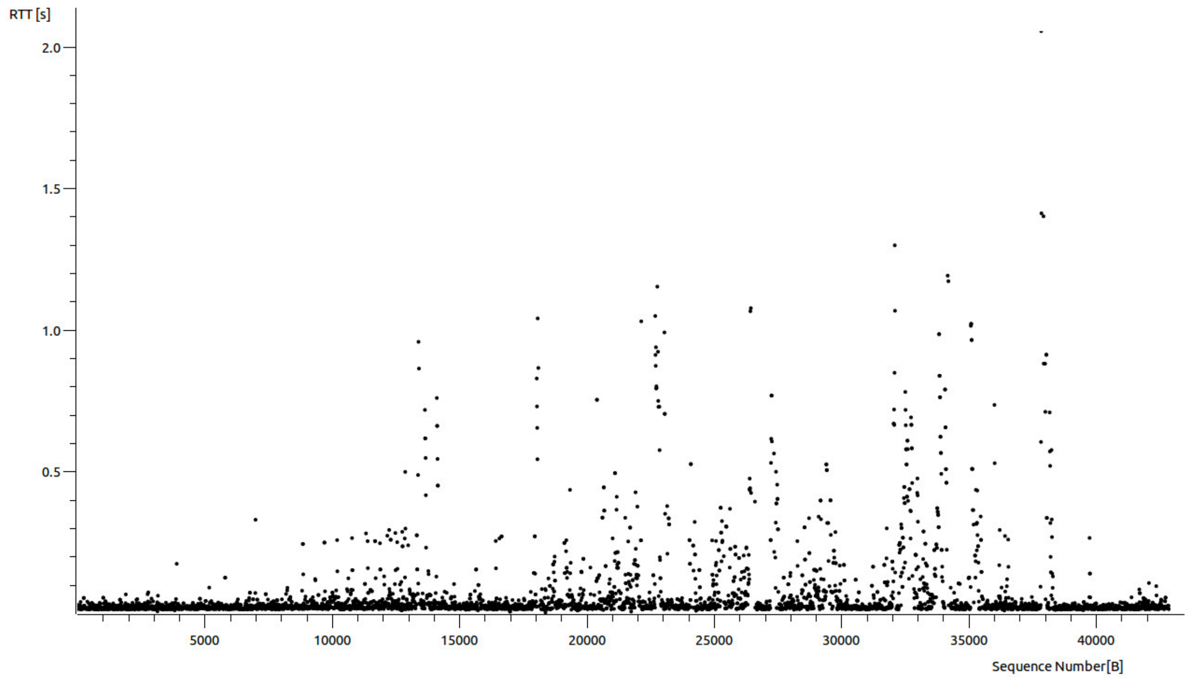

Figure 5: In the physical experiments, the round trip times reached 2s.

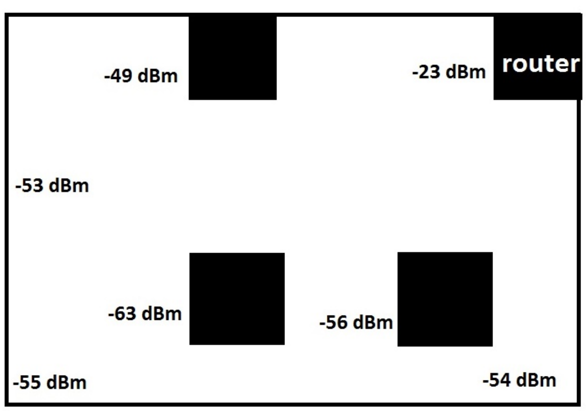

Figure 3: The signal strength was gathered from the outdoor environment. There was more signal attenuation, or loss in strength, behind the concrete obstacles.

fects of wireless network issues on a cooperative multirobot system. Controlling a team of robots can be difficult in a controlled environment, but in a dynamic, noisy, or unpredictable environment, overcoming it can be even more challenging. In such environments, there are many variables that can not be controlled (i.e. weather, interference) that affects signal propagation and attenuation.

While the effects of communication limitations on robot teams is important, it is worth investigating new ways to coordinate robots in extreme or dynamic environment. After all, there are many aspects of exploration applications in the real world that can not be predicted or controlled including the reliability of the communications network.

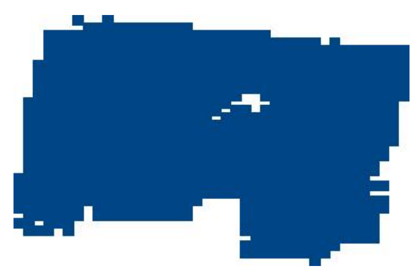

Figure 6: In simulation, the robots covered more of the area in 10 minutes.

Perhaps, the answer is in applying artificial intelligence methods to make robots more adaptable. One approach on the rise is evolutionary robotics. Generally, in evolutionary robotics, the controllers are evolved in simulations and then transferred to real robots. Although, studies using evolutionary methods are promising, there is limited research on physical multirobot systems.

Another topic that should be considered is developing robotic simulators with realistic models of wireless communications networks. In most simulators, network and environmental conditions are optimized. Therefore, there can be discrepancies between simulation and physical robot experiment results. Providing more realistic simulators could give more confidence of coordination algorithm for real world use.

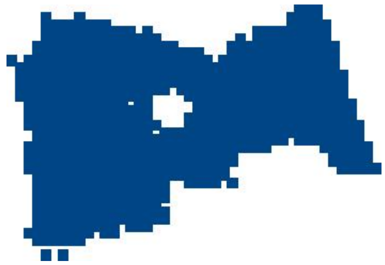

Figure 7: In physical experiments, robots had a slower coverage rate than in simulation.

Conclusion and Future Work

In this work, we investigate the effects of signal strength and attenuation on robot team performance. Signal propagation is affected by many factors such as distance between robots, obstacles, materials of the environment, interference and weather. Simulation results were compared to physical experimental results. Results suggest that weakened signal strength does affect team performance. Future works includes varying the number of robots and environments. It also includes applying artificial intelligence methods to make robots more adaptable to their environment.

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