

Protocols and Applications of Ad-hoc Robot Wireless Communication Networks: An Overview

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Abstract- Communications and communication protocols play an important role in mobile robot systems. They enable the latter to address many real world applications. Since the advent of high-performance wireless local area network (WLAN) and ad hoc networking technology at relatively low cost, their use for wireless communications among mobile robots has become a practical proposition. However, in a large system with many mobile robots, it becomes difficult for all robots to exchange information at a time because of their limited communication capacities. In this case, an ad-hoc robot networking scheme is more promising. This paper focuses on this scheme by presenting the background of mobile ad hoc networks, ad-hoc robot wireless communications, and their applications. It serves readers with a comprehensive review of ad-hoc robot wireless communications and indication of the future research issues.

Index Terms—Robot communication, ad-hoc network, protocol, power efficiency.

1. INTRODUCTION

As VLSI technology advances and computing power grow in the past decades, robots became more and more intelligent, robust and power-efficient. They are required to handle more and more so-called teamwork. It means that they must be developed to possess the capability of constructing a network and performing cooperative work. A key driving force in the development of cooperative mobile robotic systems is their potential for reducing the need for human presence in dangerous applications [Dias, 2005][Sibley, 2002][Parker, 1998]. The elements of danger clearly exist in such applications as the disposal of toxic waste, nuclear power processing, fire fighting, military or civilian search and rescue missions, planetary exploration, security, surveillance, and reconnaissance tasks. In these cases, wireless communication provides the low cost solutions for mobile robot networks to cooperate efficiently.

In the early robot wireless communications, infrared technology was applied in a large scale [Kahn 1997; Hsu 1995] because of its low cost. But infrared wave cannot pass through obstacles (e.g. wall) and infrared systems have poor communication rate and quality (rain effect). Radio frequency (RF) technology is more preferred in the

design of mobile robot communication. Robots can communicate with others by RF point-to-point link or broadcasting mechanism [Chlamtac 1985]. The frequency hop spread spectrum (FHSS) and direct sequence spread spectrum (DSSS) modulation technologies are extensively applied at the Industrial Scientific Medical (ISM) band (2.4 GHz), which is license-free in many countries [Britland 1995] [Arai 1993]. The proliferation of Internet-like networks has motivated the research to address wireless LAN (IEEE 802.11), Bluetooth standards, and ad hoc networking fashion in mobile robot systems [Basagni 1999][Genovese 1992]. Figure 1 shows the evolution of robot wireless communication. Table 1 compares wireless communication technologies that are available for mobile robot communication.

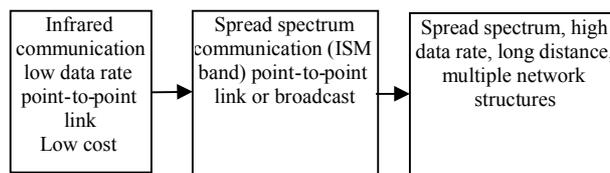


Fig. 1. The evolution of robot wireless communication.

Table 1. Wireless communication technologies for mobile robots

	Infrared	IEEE 802.11b	Bluetooth
RF band (GHz)		2.4/5	2.4/5
Modulation		DSSS	FHSS
Data rate (Mbps)	0.1- 4	11 (shared)	0.72 future 10/20
Range (m)	4	30-1000	10-100
Network structure	PPP	Infrastructure and ad hoc	Ad hoc
Power	5 mw	<=1w	0.3mw-30mw

The wireless communication link is characterized by long bandwidth-delay, dynamic connectivity, and error-prone transmission. The robots are often equipped with low-cost low-power short-range wireless network interfaces, which only allow direct communication with their near neighbors. Hence, it is virtually impossible for each node to know the entire network topology at any given time. Under these circumstances the only practical approach to distributed command, control and sensing is

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to employ an ad hoc wireless networking scheme [Winfield 2000].

In contrast to a WLAN network that needs some base towers, an ad hoc network is an infrastructure-less network where the nodes themselves are responsible for routing packets. Mobile nodes communicate with each other using multihop wireless links. There is no stationary infrastructure, e.g., no base stations. Each node in the network also acts as a router, forwarding data packets for other nodes. Furthermore, because the topology in such a network can be highly dynamic, traditional routing protocols can no longer be used [Perkins, 1999].

The design of ad hoc networks has focused on the development of dynamic routing protocols that can efficiently find routes between two communicating nodes. The routing protocol must be able to cope with the mobility of nodes, which often changes the network topology drastically and unpredictably. Recently there was a renewed interest in this field due to the common availability of low cost laptops and palmtops with radio interfaces. A mobile ad hoc networking (MANET) working group was formed within the Internet Engineering task force (IETF) to develop a routing framework for IP-based protocols in ad hoc networks.

This paper proceeds as follows. First it reviews MANET and its routing protocols in Section 2. Section 3 discusses the protocol stacks and explains why ad hoc networking is practicable for mobile robot wireless communications. Section 4 illustrates some applications. Finally, Section 5 concludes the paper.

2. BACKGROUND OF MANET

MANET is the collection of mobile nodes that form a temporary network. The network often has a dynamic and unpredictable topology. In such a network there is no centralized administration or standard support services. Moreover, each host is as an independent router. Hosts use wireless RF transceivers as network interface. They have limited bandwidth, power supply, and limited transmitter range. The network allows multiple radio hops but it lacks of symmetrical links. Ad hoc routing protocols can be broadly categorized into proactive and reactive protocols [Royer 1999].

Proactive Routing Protocols

Proactive routing protocols have the characteristic of attempting to maintain consistent up-to-date routing information from each node to every other node in the network [Shah 2002]. Every node maintains one or more routing tables that store the routing information, and topology changes are propagated throughout the network as updates so that the network view remains consistent. The protocols vary in the number of routing tables maintained and the method by which the routing updates are propagated. Two common proactive protocols among many are briefly discussed.

Destination-Sequenced Distance-Vector Routing protocol (DSDV) [Perkins 1994] is based on the Bellman-Ford algorithm for shortest paths and ensures that there is no loop in the routing tables. Every node in the network maintains the next hop and distance information to every other node in the network. Routing table updates are periodically transmitted throughout the network to maintain table consistency.

Link-State Routing (LSR) [Jacquet 2002] is a proactive protocol in which each node floods the cost of all the links to which it is connected. Every node calculates the cost of reaching every other node using shortest path algorithms. Moreover, the protocol can work correctly even if one-way links are present while DSDV assumes two-way links.

Reactive Routing Protocols

In contrast to proactive ones, reactive protocols create routes only when desired. This means that an explicit route discovery process creates routes and this is initiated only on an as-needed basis [Shah 2002]. It can be either source initiated or destination-initiated. Once a route has been established, the route discovery process ends, and a maintenance procedure preserves it until the route breaks down or is no longer desired. Ad-Hoc On-Demand Distance Vector (AODV) routing protocol is a reactive one although it is based on the distance vector algorithm like DSDV. It is a source-initiated protocol, with the source node broadcasting a Route Request (RREQ) when it determines that it needs a route to a destination and does not have one available. This request is broadcast till the destination or an intermediate node with a "fresh enough" route to the destination is located. Intermediate nodes record the address of the neighbor from which the first copy of the broadcast packet is received in their route tables, thus establishing a reverse path.

Dynamic Source Routing (DSR) [Johnson 1996] uses source routing rather than hop-by-hop routing, with each packet to be routed carrying in its header the complete, ordered list of nodes through which the packet must pass. It consists of two mechanisms: Route Discovery and Route Maintenance. To perform the former, the source S broadcasts a route request packet that is flooded through the network in a controlled manner and answered by a route reply packet from either the destination node D or another that knows a route to the destination. To reduce the cost, each node maintains a cache of source routes it has learned or overheard. This node uses cache to limit the frequency and propagation of route requests. By Route Maintenance, S detects if the topology has changed to break its route to D because two nodes listed in the route have moved out of range of each other. When it indicates that a source route is broken, S is notified with a route error packet. S must then attempt to use another route to D already in its cache or invoke Route Discovery again to find a new route. With DSR, intermediate nodes do not need to maintain up-to-date routing information in order to route the packets they forward, since the packets

themselves already contain all the routing decisions. This feature, coupled with the on-demand nature of the protocol, eliminates the need for the periodic route advertisement and neighbor detection packets.

Labeled Distance Routing (LDR) [Garcia-Luna-Aceves 2003] is an improved version of AODV in terms of the way to use sequence numbers. It is based on a dual invariant consisting of destination sequence numbers and feasible distances. A feasible distance measures the smallest distance to a destination attained by a node for its current sequence number for the destination. The destination sequence number is used to "reset" the distance to a destination, i.e., to allow a node to accept a next hop that reports a distance larger than the node's feasible distance. The use of feasible distances makes LDR more likely for its nodes other than the destination to resolve route requests, thereby improving the performance.

Feasible Label Routing (FLR) [Rangarajan 2004] is the first on-demand routing protocol that uses path information only in its signaling, while supporting loop-free incremental forwarding of data packets when the header of each data packet contains only the address of its intended destination. FLR enables loop-free incremental routing of a data packet using only the address of its destination. Like DSR, it does not need any time-stamps or sequence numbers by using path vectors exchanged when routes are established or repaired. It achieves instantaneous loop freedom by using path information for a destination as labels with which routers are ordered lexicographically with respect to the destination. It outperforms such protocols as AODV and DSR.

Sensors-enabled event routing architecture (SEERA) [Yu 2005] implements an environment monitoring system based on sensor networks. It adopts a two-tier hierarchical clustering architecture including an adaptive clustering technique and multi-hop routing protocol. In tier-1, SEERA functions as a hybrid MAC protocol that consists of both contention and schedule. The cluster member nodes contend for a fixed number of slots. The clusters are formed in order that both the intra and inter-cluster communications require the lowest amount of transmission power. In tier-2, SEERA functions as a lightweight multi-hop routing protocol, which combines AODV and energy-efficient routing protocols. The optimal route is chosen based on the energy consumption and residual power at each node along the route.

In conclusion, proactive routing protocols can be deployed in a small-size and topology-slowly-changing network. The routing packets needed by protocols would not add too much load to the network under this situation. However, a reactive protocol may be more suitable for a large scale and fast topology-changing network because the routing tables that are maintained at each node should be small compared to the size of the network to avoid requiring large caches. A large network can often be divided into some small subnets. Then both proactive protocols and reactive protocols can co-exist. For example,

proactive protocols can be used in subnets while reactive protocols are used among subnets.

3. MOBILE ROBOT COMMUNICATION NETWORKS

3.1 Mobile Robot networking layered model

Mobile robot wireless networks provide the networking infrastructure to support the quality of service (QoS) needs (bandwidth, latency and reliability) of robot communications. They must support: quick reconfiguration (802.11, token ring [Sugiyama, 2000]), mobility management (mobile IP, AODV) [Basu 2004], service level agreement (SLA) management, and QoS (mobile Internet Protocol). Figure 2 gives a layered model of mobile robot networking. It has transport, network, data link, and physical layers.

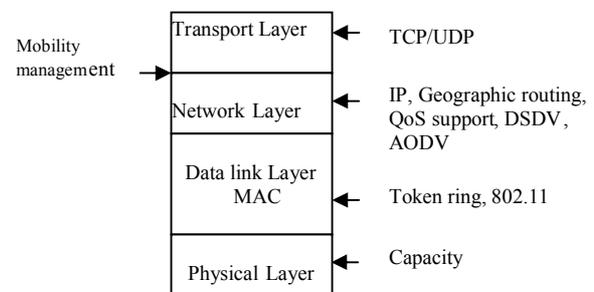


Fig. 2. Mobile robot networking layered model.

In the system of cooperative multiple mobile robots, communications among them are critically important. Each robot should exchange the information collected through its sensors and negotiate its task scheduling with other robots. These robotic communications are executed through the random access telecommunication among mobile robots. Experiments of robotic communication among several robots are reported using wireless LAN or infrared sensory systems [Sibley, 2002] [Das, 2005][Alami][Sugar 1999][Basu 2004]. Wireless LAN devices that make use of spread-spectrum modulation and a UHF carrier (typically 2.4 GHz) offer the potential for high message data rates over a reliable physical layer implementation. Specially, the model called Murdoch [Gerkey 2001] used a publish/subscribe messaging model to coordinate autonomous robots. However, the applicability of these systems to a large number of robots remains to be demonstrated. A modified cellular system for wide range robotic communication is proposed in [Adachi 1998]. However, the communication service area is restricted by the positions of base stations.

3.2 Why ad-hoc networking?

Consider a group of mobile robots that are required to autonomously disperse throughout a region, perform

distributed sensing, monitoring or surveillance, and pass the sensed data to a single collection point. The robots are most likely equipped with only low power wireless transceivers whose range is too short to allow direct communication with the data collection point, but sufficient to allow robots to communicate with close neighbors. These circumstances qualify an ad hoc wireless networking scheme as a unique choice.

The disadvantages of centralized control for robot teams are apparent as one may have observed in "Star Wars Episode I: The Phantom Menace". The bad robots had a single centralized point of failure. A whole army was rendered useless when their controlling computer was destroyed [Vaughan 2001]. This example clearly suggests that centralized control and communication could more easily lead to a fatal system breakdown. In other words, robustness may be low. Secondly, designers may not prefer a centralized system due to the design and cost consideration. To guarantee a certain level of QoS, expensive base stations are required to cover the service area. Therefore, complex system management obviously increases the total cost of a system. On the other hand, decentralized and distributed systems based on local interactions among autonomous nodes support ad-hoc changes in population, connectivity and local constraints. They show robustness to local failures and scale very well and are sufficient for most applications. The real-world ARPAnet was conceived as protection against the Star Wars scenario. The success of its subsequent development into Internet is evidence of the power of the decentralized control and communication concept.

In unpredictable or unplanned environments mobile robots need to create a wireless network to cooperate and schedule tasks. Multihop ad hoc networks capable of self-creation and self-organization become a natural choice used to meet such needs.

3.3 Energy-optimized protocols

Because mobile robots are mainly dependent on battery power, it is important to minimize their energy consumption. This paper only discusses the communication subsystem of mobile robots. The two concerned layers are the media access control (MAC) and network ones.

Media Access Control (MAC) Layer

The MAC layer's primary functions are to provide access control, channel assignment, and neighbor list management. It also performs power control to ensure power savings. The main principles guiding low power distributed MAC design include collisions avoidance, reduced protocol overhead, and power-off during idle time. First, collisions should be avoided since retransmission leads to unnecessary energy consumption and possibly unbounded delays. Secondly, protocol overhead should be reduced as much as possible, including packets dedicated for network control and

header bits for data packets. Thirdly, since receivers have to be powered on at all times resulting in significant energy consumption, the more time the radio can be powered off, the greater the power savings. Researchers [Liu 2005][Wang 2005] have developed some energy-aware MAC protocols: Power-Aware Routing in Mobile Ad hoc networks (PAMAS) schemes, time-division media access (TDMA) and the 802.11 specification.

A major source of extraneous energy consumption is from overhearing [Das, 2005][Singh 1998]. In PAMAS, the radio of a node is powered off when it is not actively transmitting or receiving packets. In Fig. 3, node A's transmission to B is overheard by C because C is a neighbor of A. PAMAS avoids the overhearing problem by powering off C. Thus C spends no energy in receiving a packet that is not sent to it. But PAMAS does not address the problem of energy consumption when nodes are idle. The work [Xu 2001; Stemm 1997] shows that idle energy dissipation cannot be ignored in comparing to sending and receiving energy dissipation. [Liu 2005] proposed a method using space and time combining to solve the packet collision caused by radio interference.

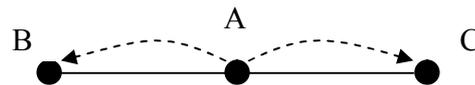


Fig. 3. An overhearing problem.

TDMA [Pottie 2000] protocols have been proposed to reduce energy consumption in sensor networks. By reducing the duty cycle, these protocols can trade idle-time energy consumption for latency. However the conclusion holds only when radio also runs at a lower data rate.

Through estimating the future movement of objects and analyzing the tradeoff between the estimation cost and the quality of reliability, Guo et al. [2005] optimize the tracking interval for sensor networks. A quantitative analytical model is proposed to find such an optimal tracking interval by studying the effect of the tracking interval on the miss probability and exploiting the tradeoff between the accuracy and cost of sensing operation. It describes the predictive tracking sensor network architecture, and presents the predictive accuracy-based tracking energy saving scheme. The method is effective in saving energy in sensor networks.

IEEE 802.11 supports power saving mode in both infrastructure and ad hoc networks: mobile nodes are brought together to form a network on the fly. 802.11 also provides power management controls to allow disabling a transceiver to conserve energy. Although they specify how to turn off the radio, they do not discuss specific policies.

Network Layer

Addressing, routing and support for different classes of service are the primary functions of the network layer. This paper only concentrates on a routing issue. Some

routing protocols of ad hoc network were discussed in the previous section. They are traditionally evaluated in terms of packet loss rates, routing message overhead, and bandwidth utilization. They have not paid much attention to robot-oriented ad hoc routing protocols. A number of energy-conserving protocols for ad hoc routing have been proposed [Das 2005; Xu 2001; Shah 2002; Intanagonwiswat 2000; Ko 1998]. This paper examines some recent studies: Directed Diffusion, Location-Aided Routing (LAR), Geographical Adaptive Fidelity (GAF), and energy aware routing.

Directed Diffusion [Intanagonwiswat 2000] is a destination-initiated reactive protocol. A destination node (controller) broadcasts its interest in certain data, and the source node reply back, setting up multiple paths to the destination in the process. Due to the multiple paths created, the scheme assures data flow in the event of node failure. However, diffusion requires the use of large caches at every intermediate hop.

LAR utilizes location information to improve performance of routing protocols in ad-hoc networks [Ko 1998]. They use location information to decrease overhead of routing discovery by limiting the search space for a desired route. But sometimes positioning information is not easily accessible, and then LAR may be affected by moderate location error or even by large, correlated error.

GAF is compatible with LAR as it is with other ad hoc routing protocols [Xu 2001]. GAF's approaches to energy savings are implemented by state transitions of nodes. An active node can enter *sleep* state once its energy decreases to a pre-defined level. It can also enter discovery state to update topology changes by setting an appropriate timer. GAF can balance load (energy usage) and adapt to high mobility. However, determining node equivalence by means of virtual grids is complex and difficult. Additionally, if a node is actively routing packets when it is powered off, GAF depends on the ad hoc routing protocol that allow quickly re-routing traffic. This may cause some packet loss.

The basic idea of energy aware routing is to increase the survivability of networks. Multiple paths are found between source and destinations, and each path is assigned a probability of being chosen, depending on the energy metric. Every time data is to be sent from the source to destination, one of the paths is randomly chosen depending on the probabilities. This means that none of the paths is used all the time, preventing energy depletion. Energy aware routing is also a reactive routing protocol and similar to diffusion. However, diffusion sends data along all the paths at regular interval, while energy aware routing uses only one path at all times. But due to the probabilistic choice of routes, it can continuously evaluate different routes and choose the probabilities accordingly.

The potential problem in the current protocols is to find the lowest energy route and use that for every communication. Yet this is not the best thing to do for network lifetime. Using a low energy path frequently

leads to energy depletion of the nodes along that path and in the worst case may lead to network partition [Shah 2002]. Energy aware routing is a promising protocol but more experiments and actual traffic scenarios are still needed. Since an ad hoc network works in a multihop way, the protocol overhead should be adequately small and then would not waste too much power. A trade-off exists between routing robustness and energy conservation. In some non-real-time applications, data packets could be buffered in caches and burst them in a combined packet, increasing the latency, but reducing the total energy consumed. Apparently, energy conservation should be considered not only in MAC and network layers, but also in application-level. Integration of energy conserving consideration in multi-layers requires the future work.

A tight integration between network, mission and motion control can compose a unified Energy-Conserving Protocol Stack for future developed Small-Scale Robots. This allows a substantial energy savings while keeping delay and throughput requirements within application constraints. The next subsection will discuss such integration.

3.4 Robot control and communication strategies

Successful control and coordination of a group of wireless-networked robots relies on effective inter-robot communication [Ye 2001]. Robot controllers should be robust with respect to unpredictable and highly dynamic environment; due to the naturally hostile characteristic, controllers must also contend with imperfect wireless communication. Apparently the network is also part of the robots' environment and can contribute to the system's success or failure. At the simplest level, communication may succeed or fail between two nodes.

Robots typically operate under strict real time constraints [Gerkey 2001][Ye 2001]; fast navigation and dynamic environments require that control inputs are acquired in a timely manner. Heavy load on a wireless network increases the average data transmission time, and reduces the frequency response of controllers. Thus it may reduce the capability of the controller. Reducing load by more efficient communication can decrease latency and allow robots to be more responsive to dynamic environments.

Bandwidth is a precious resource if a robot's task involves transmitting huge data to a user (e.g. live video). Controller data is unwelcome overhead on the shared communications channel [Gage 1993]. Efficiency becomes increasingly important when scaling to a large numbers of nodes. Efficient communications are essential to save power and reduce latencies. It can be achieved by considering the interaction between controller and communication channel; controllers should be designed to take into account protocol characteristics and propagation conditions, and specialized protocols can be designed for mobile robot applications [Gerkey 2001][Ye 2001]. An example application in which a team of mobile robots

explores an initially unknown environment to locate a supply of resource [Ye 2001] is used to illustrate such needs.

4. APPLICATIONS

Robot communication applications choose ad hoc networks when central bases are not available and/or a strong need arises to avoid the vulnerability of centralized infrastructure. In the following applications, they can be used to improve the robustness, scalability, and performance of a multi-robot system.

Robot soccer games

In [LCA 2002][RobotOz 2002][Murata 2002], different types of robot soccer players take part in some official robot soccer games organized by various robot soccer organizations. For example, FIRA Cup, CENDORI and SOCCERBOT allow the robot team to deploy the wireless LAN devices that are based on 802.11 standard. Bluetooth ad hoc network is adopted to coordinate the team performance [Murata 2002].

Explosive ordnance or hazardous materials disposal

In the Mobile Detection Assessment and Response System (MDARS) project [Gage, 1997], mobile robots were organized in a centralized way in a large warehouse near San Diego to detect intruders and anomalous conditions such as flooding or fires. It was proved that an ad hoc network could provide more flexibility and robustness in a highly mobility environment than WLAN.

Rescue and recovery operations

Robot teams can play an important role in disaster recovery such as earthquake rescue operations or nuclear plant accidents. By means of ad hoc networks, robots can coordinate their activities with reliable communication regardless the conditions of all fixed infrastructures. This area becomes more and more important.

Unmanned Vehicles

Unmanned Aerial Vehicles (UAVs) and Unmanned Marine Vehicles (UMV) are emerging as a viable and cost effective alternative to space and ocean surveillance. These teams must operate in remote regions with little or no infrastructure. Hence, the autonomous teams of UAVs and UMVs are organized into a MANET. Such configurations can result in relatively stable topologies and thus robust communications.

Planetary and volcano exploration

NASA developed many robots such as Pathfinder, Robonaut for Mars exploration or other space journey; Dante is a volcano explorer robot. More studies are needed to investigate if ad hoc networking is feasible [Weisbin, 2000] for such environments.

5. CONCLUSIONS

Ad hoc mobile robot communications are a promising networking technology. Yet ad hoc robot communication represents a relatively underdeveloped application field. The paper discusses ad hoc protocols and analyzes energy conservation routing protocols whose system performance metric is energy saving. Other metrics such as connectivity, throughput, accuracy, security, robustness and bandwidth efficiency, should also be considered in measuring the system performance. In the design of wireless robot networks, we need to evaluate overall performances with respect to practical requirements. In an energy-constrained environment, protocols should pay more attention to energy consumption, but for a real time image-sensing task, system throughput and bandwidth utilization are more important. Therefore, different protocols need to be developed to optimize different metrics for different applications. Moreover, future research is required to develop prioritized protocols so that a system can deploy protocols according to the priority of performance metrics in real time. Additional work is needed to ensure secure communication. Good tradeoff between security and performance requirements must be carefully made. This field clearly requires significant research efforts.

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