ROP: A Resource Oriented Protocol for Heterogeneous Sensor Networks

Yong Ma*, Siddharth Dala1**, Majd Alwan**, James Aylor*

(ym3f, dalal, ma5x, jha)@Virginia.edu

**Medical Automation Research Center
University of Virginia Health System
Charlottesville VA 22908

*Department of Electrical and Computer Engineering
University of Virginia
Charlottesville VA 22904

ABSTRACT: *Sensor networks have been an active area of research during the past several years. Much previous work deals with issues related to networks having homogenous sensor nodes. In reality, sensors with different radio coverage, power capacity, and processing capabilities are deployed. In addition, not all of the sensors are mobile or have the same mobility freedom or mobility attributes (e.g. speed). The architecture and routing protocol for this type of heterogeneous sensor network must be based on the resources and characteristics of their member nodes. In this paper, we propose a network model that is adaptively formed according to the resources of its members. A protocol named Resource Oriented Protocol (ROP) was developed to build the network model. This protocol principally entails two phases. In the topology formation phase, nodes report their available resource characteristics , based on which network architecture is optimally built . We stress that due to the existence of nodes with limitless resources, a top-down appointment process can build the architecture with minimum consumption of resources. In the topology update phase, mobile sensors and isolated sensors are accepted into the network with an optimal balance of resources. To avoid overhead of periodic route updates, we use a reactive strategy to maintain route cache. This paper provides encouraging simulation results of ROP in GlomoSim.*

1. Introduction

Recent advances in microelectronics and wireless communications have enabled the development of low cost, low power, high integration and small size wireless sensor nodes, which can be networked into wireless sensor networks, to implement some new and exciting tasks. Wireless sensor networks represent a significant improvement from traditional sensor networks. Sensors can communicate and cooperate with each other via wireless means. These networks have the added advantages of faster deployment and reduced deployment cost, particularly into existing structures.

However, such wireless sensor networks do have unique challenges. Sensors typically have limited resources related to energy capacity, computational power, storage space, and processing capability. Communication between these sensors is susceptible to failure due to sensor malfunction or radio transmission problems related to change of positions. Moreover, due to large-scale deployment of sensors and common transmission media, interference among sensors can be significant. Consequently, successful protocols have to take all these constraints into account.

To evaluate performance of protocols for sensor networks, several metrics have been proposed [1]. Among these, energy efficiency was identified as the key component. System lifetime is also considered as an important metric. These two metrics may seem similar, but in actuality they are different. As we know, most sensors in sensor networks have limited energy capacity. This requires protocol stratagems that use this energy efficiently. By efficient management of energy usage, system lifetime is lengthened. However, this may not always be true in practice. For example, in home-like environments outfitted with wireless sensors for monitoring applications, some sensors may connect to power lines. These sensors can serve as powerful cluster heads ignoring power consumption. In this case, equal stress on energy efficiency for all sensors may reduce the system lifetime and overall network performance. In other words, protocols can utilize the limitless energy of powerful sensors to reduce energy consumption of energy-constrained sensors. Although more energy may be consumed in total, system lifetime is lengthened.

Moreover, in many applications, sensors are heterogeneous in terms of resources they possess. For instance, in a smart home environment sensors may be powered by AA batteries, AAA batteries or even button batteries. It is obvious that sensors with larger resources can take on more tasks. Even for some applications that use homogeneous sensors at the beginning of deployment, sensors will become different in energy capacity after some time, as energy consumption is not always equal in all sensors. Therefore, because of the nature of heterogeneity, the network model should be adaptive to the resources available to its sensors.

In this paper, we present a Resource Oriented Protocol (ROP) that takes specific characteristics of sensors into account and implements a network topology accordingly. This protocol is originally intended for sensor and actuator network for monitoring and automation applications in home-like environments, such as Smart Homes, but has industrial and security applications as well. The protocol entails two phases: topology formation phase and topology update phase.

In the topology formation phase, sensors report their characteristics and available resources. This information allows the network architecture is optimally determined. We stress that by exploiting the existence of sensors with essentially limitless resources, an optimal topology forms with minimum consumption of resources in resource-constrained sensors. In the topology update phase, mobile sensors and isolated sensors are accepted into the network with optimal balance of resources. Meanwhile, route cache is maintained reactively avoiding communication overhead of periodic update methods.

The remainder of the paper is organized as follows: in section two, some theoretical analysis is provided. In sections three and four we detail the two phases of ROP. In section five simulation results are presented. Some previous work in this area is reviewed in section six. Finally, we present conclusions in section seven.

2. Scenario analysis

Literally, “heterogeneous” means different in some aspect. In our discussion of heterogeneity we refer to sensors having different resources. Heterogeneous sensor networks have many applications. In home-like environments outfitted with a wireless sensor network for monitoring or home automation applications, sensors with different energy capacity are deployed. The energy capacity ranges from around 100 mAh (button battery) to infinite (mains-powered). Similarly, in battlefield, sensors installed on tanks have much more energy capacity than those carried by individual soldiers. However, the protocol described here is primarily intended for sensor networks in home-like environments, but does have further application potential.

2.1 Hierarchical structure

Usually sensor networks have a large number of sensor nodes. In these networks, there may exist two sensors that are very far away from each other, with many sensors between them. An example is two sensors at two ends of a network. Although messages can be sequentially transferred from one sensor to another to complete communication, the time required for the message to travel may be too long. We define this problem as “two-end” problem

Hierarchical structure of the network can reduce or resolve the “two-end” problem. The structure requires that some capable sensors act as local cluster heads and simultaneously interface with the outside world. Clustering of sensors can also aggregate and process data locally to reduce communication load in the network. However, this solution may not be energy efficient. It is well known that radio transmission power is proportional to d^{-n}, where d is the distance between two transceivers and n is the path loss exponent, usually $2 <= n < 4$ [2]. Hence, to have the same power level at the receiver end, transmission power should be proportional to d^n.

$$P_s = k \cdot d^n$$

If N-1 intermediate sensors are inserted between the two sensors equidistantly, the total transmission power P_N can be described as follows:

$$P_N = N \cdot k \cdot (d/N)^n$$
$$= P_s / N^{n-1}$$

Therefore, total transmission power decreases exponentially with increasing hop-number *N*. Moreover, participant sensors share the consumption of power equally. The result indicates that assigning a cluster head to be the communication hub and cover a larger area is not energy efficient. However, in heterogeneous sensor networks, this effect is negligible. Noticeably, if *N* and *n* are small, the exponential effect is not significant. In a heterogeneous sensor network, cluster heads of sensors are close, which means smaller *N;* sensors normally have clear line-of-sight path, which means the path loss factor can also be small. Furthermore, as mentioned earlier, multi-hop communication without clustering consumes equal energy among all participant sensors, which result in faster energy exhaustion of sensors with lower energy capacity. With cluster heads taking more responsibility, energy consumption is saved for sensors with more constrained energy resources, which extends the lifetime of the whole network.

2.2 Powerful Relay Center

Sensors in sensor networks are usually perceived as resource constrained, but in practice there are some sensors that have essentially limitless resources. In home-like environments, for instance, some sensors may be connected to the power mains line. These sensors have limitless energy backup, which provides an advantage for routing protocols to conserve energy of more resource-constrained sensors. As Fig.1 shows, D and E are more energy-constrained sensors and D attempts to send a message to E. A and B are battery-powered cluster heads. C is a sensor that is powered by mains. Normally, the message will go through F, G and B to E. However, due to the existence of C, the path can turn from A to E through C.

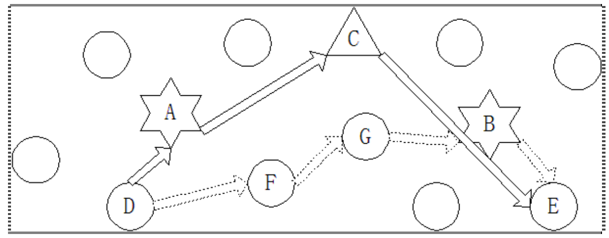

Fig. 1. Powerful Relay Center

We call sensors like C powerful relay centers and denote as LRCs, an acronym for sensors with Large Resource Capacity. Since LRC can accomplish communication from top to bottom, sensors only need to maintain a route to a LRC. It is clear that a communication path from a source to a destination is different from the return path. For example, the route from E to D goes from E to B to C and then directly to D.

2.3 Two Phases: Topology Formation and Update

ROP entails two phases. In the topology formation phase, we build an architecture based on the resources available to the sensors. We avoided using pure selection to cluster sensors because selection needs negotiation between sensors, which needlessly consumes energy. Additionally, selection usually does not take into account the overview of the whole network and hence cannot distribute resources and tasks accordingly. As we mentioned, LRCs have limitless energy, so during this phase LRCs take a major role to organize the network. We use local report and top-down appointment to form the topology.

After the topology is built, sensors have proactive routes. Proactive routing protocols exhibit a sizable overhead of route maintenance, as periodic messages have to be broadcasted to update route information. In contrast, in the topology update phase, ROP uses a reactive scheme to avoid broadcasting messages periodically. Only when a sensor needs to send a message will it check the route information and if it is corrupted, a route request message will be sent out. We emphasize that not all of sensors are mobile in our targeted applications. Thus, a combination of proactive and reactive routing scheme can allow us to take advantage of the benefits of both schemes.

3. ROP: Topology Formation

Since the topology formation process takes a very short time compared to the anticipated speed of mobile sensors, we assume all nodes are static, namely, having fixed position during topology formation. Once the topology is formed the mobile sensors may move and the topology will dynamically restructure itself.

Topology formation involves two steps. The first step is a reporting step where each sensor reports its individual characteristics to all of its neighboring sensors. The local cluster head then reports this aggregated package to the most powerful sensors. In the second step, those powerful sensors decide the topology of the network. Based on this topology, sensors appoint cluster heads at next level and so on.

3.1 Reporting Phase

Before the beginning of the process, sensors are deployed without having information about their neighbors and what resources are available for these accessible sensors. Therefore, sensors have to report their resources to neighboring sensors by local clustering and to the most powerful sensors by reporting their aggregated package.

3.1.1 Local Clustering

Each sensor reports its local characteristics to all sensors within its range, including the sensor's unique identifier. The report consists of characteristics such as but not limited to energy capacity, radio coverage range and computational potential. Based on their own characteristics and the characteristics of reports received from their neighbors, sensors will classify themselves into several levels. As an example, based on energy capacity, sensors can be divided into three levels: Small, Medium or Large. To simplify formulating our protocol, we demonstrate the principle on three different levels of resource capacity and denote sensors according to their resource as SRC (Small Resource Capacity), MRC (Medium Resource Capacity) or LRC (Large Resource Capacity). In practice, the levels can be as many as the application requires.

If a sensor receives reports from only sensors with similar or larger resources, it will classify itself as a SRC. If a sensor receives reports from both smaller and larger resource sensors, it will classify itself as a MRC. Sensors with very large resources (for instance, mains powered sensors or sensors powered by comparatively high capacity batteries) and receiving reports from sensors of vastly small resource will classify themselves as LRCs.

After receiving packages from all its neighbors, a sensor will store the packages and keep them until the whole topology forms. It is noteworthy that sensors do not forward the report packets. Consequently, traffic is only in the local area and the network will not be unnecessarily flooded with packets. It is the local cluster head's responsibility to send an aggregated package about its cluster to a LRC. At this step, MRCs will automatically act as temporary local cluster heads.

3.1.2 Aggregated Package Report

After receiving packages from neighbors, MRCs aggregate these reports and build a package called MRC's Neighboring Sensors (MNS). This package contains information of all sensors in a cluster and their resources.

Before MRCs send their aggregated package out, LRC will first send a package (LRC's Neighboring MRCs or LNM) to list the neighbors it can directly communicate with. This can reduce traffic for requesting route to a LRC and save energy of intermediate sensors.

If a MRC is a neighbor of a LRC and is listed in the list of LNM, it will send its MNS directly to LRC. If a MRC is not in the list of LNM but it has a neighboring sensor that is included in the list, it will take a route through this neighbor, and will use this route to send its MNS package.

There may exist some MRCs that do not fall in either of the above two cases. To get a route towards a LRC, these MRCs have to send a route request package (RREQ) to request a route. Any MRC receiving this request must check if it has the route to the LRC. If so, it replies back to indicate that it can be the next hop for the route. If not, it will send its own RREQ. Finally, a request reaches a sensor having a route or a LRC itself. The last sensor sends a route reply message (RREP) back to the requesting neighbor. The requesting neighbor then checks if its neighbors requested for a route before and if so replies to them accordingly. This process goes backwards until it reaches the originator MRC. After receiving the reply message, the MRC takes the route to send its MNS.

It is possible for request originators to receive several possible routes from other sensors. When several routes are received, the originator will choose the route received from the sensor with largest resources in order to exploit these resources.

3.2 Decision and Appointment

In the previous phase, all the sensors report their resource to a LRC. In this phase, LRCs will negotiate with their peers to calculate an optimal topology of the network. We take network lifetime as the criterion of optimization. After the calculation, higher-level sensors will appoint the cluster heads at the next level.

3.2.1 Topology Decision

LRC receives all the reports from MRCs and begins to decide on the network topology. If more than one LRC has the same list of neighboring sensors (in the phase of local clustering), which means they are very close to each other, one of them is chosen randomly as the highest cluster head and others will be added to the candidate list.

After the highest cluster head is chosen, it will send messages to other LRCs that are also cluster heads to compare their sensors' information. If two of them have common sensors, they assign the sensors so that a balanced structure is built. Common sensors between two LRCs indicate the two clusters have overlapped area. In such a case, sensors in the overlapped area are evenly assigned between the LRCs.

After negotiation with other LRCs, a LRC will decide the topology of its cluster. It needs to decide who are going to be the cluster heads of next level. A MRC with unique neighboring SRCs will immediately be appointed cluster heads. If two MRCs have similar neighboring sensors, the sensors will be divided so that a MRC has a number of child members that is proportional to its resource.

In case some sensors are in an associated group, the group head will automatically become a cluster head. For example, a group of sensors carried by only one person is an associated group. The sensors are kept in the group. Sensors in a group tend to move together. Hence, keeping them together will reduce overhead of updating the structure of a cluster.

3.2.2 Appointing of Cluster Heads

After a LRC calculates the topology, it sends a topology (TOP) package to notify all sensors about their routes to itself. The package contains MRCs and their corresponding child sensors. After MRCs receive this packet, they will configure their children list. After SRCs receive the package, they will setup their routes towards a LRC. A SRC stores the cluster head of its group as its route.

4. ROP: Topology Update

A topology based on resources of network sensors is constructed at this point. There are several pending issues. First, some sensors have not been included in the topology. Second, some sensors are mobile sensors, which will move to other places after some time. Thus, the route established in the previous phase has to be updated.

4.1 Isolated sensors

Some SRC nodes will not be included into the network topology described in the previous phase. These are SRCs that can reach other SRCs but cannot reach any MRC. We denote these sensors as isolated sensors. Fig.2 illustrates an isolated sensor A. A can reach B but cannot reach C, which is a MRC. As we stated in the previous section, C aggregated information of its neighboring sensors but A is not one of them.

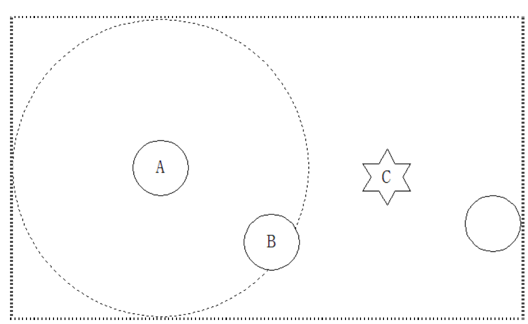

Fig. 2. Sensor A is an isolated Sensor

Although these sensors cannot reach a MRC, they can receive messages from a LRC. Therefore, after they receive a TOP, they will check if their neighbors have entries in the package. If so, an isolated sensor will choose one of its neighbors as its parent. As the above figure shows, A will find B in TOP package and will set B as its parent. If they cannot find any neighbor in the package, they will stay isolated until they want to communicate with the network, at which time they will initiate a RREQ package.

4.2 Mobile Sensors

Some sensors in the network are mobile sensors including both SRCs and MRCs. Due to movement of sensors, some sensors may lose their original routes. When a sensor wants to talk to a LRC, it will first use the route in its route cache (which is only one variable showing the next hop). If it has no such route or the route is outdated, it will initiate a RREQ package to request a route. The process is the same as we described in previous section on the aggregated package report.

4.3 Route update

Periodic updates of network topology have high communication overhead. Although in our protocol the route cache is a proactive route, we do not use periodic updates to maintain the route cache. Instead, when sensors want to communicate with other sensors, it will just use the route in its cache. If the route is outdated, it will send a RREQ package. The returned route will replace the outdated route. When several routes are received, it will choose the one with largest resources. If two routes have same resources, it will choose the one with fewer children.

Although we do not have periodic updates of route, we do reserve a scheme that helps reorganize the whole network topology. When a LRC wants to update the whole network, it will send a reorganization package (REO). A new process of ROP will then evolve.

5. Simulation Results

To test the ROP, we implemented the protocol in GlomoSim [3]. We added a new property for each node to include heterogeneous resource capacity. The MAC layer we use for our experiment is the distributed coordination function (DCF) of IEEE 802.11. The network layer is the IP protocol and we use the ROP as the routing protocol.

At the beginning of the simulation, we start the topology formation process and after several seconds, the sensor network enters normal state. In reality, although there is no start time for sensors to begin organization, we use the REO package to coordinate sensors to start together.

We use a simple example to demonstrate the functions of ROP. Fig.3 shows an application of a heterogeneous sensor networks. In an area of 2000*1000 meters, 40 nodes are randomly deployed with three levels of available resource capacity.

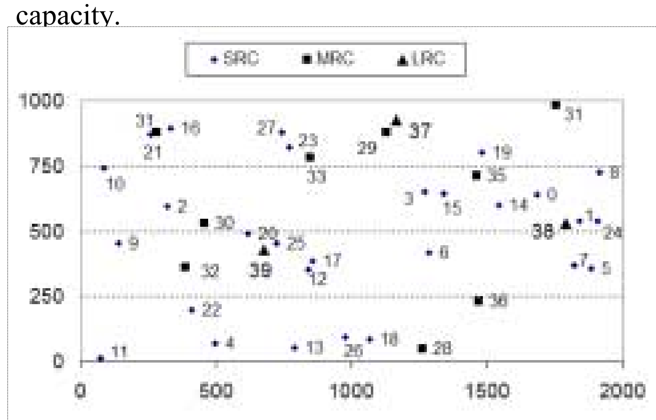

Fig. 3. A ROP application example

Three of the nodes are LRCs, 9 of them are MRCs and the rest are SRCs. We assume that sensors with larger resources can have greater coverage range. LRCs have transmission power of 20dBm, MRCs have 15dBm, and SRCs have 11dBm.

After the topology formation phase, the LRCs construct clusters as shown in Table 1. We can see that the result of the network topology is based on the resources of cluster heads. For example, LRC 38 takes all neighboring SRCs 0,1,5,7,24 as its children. It also takes 35 and 36 as its children. Node 14 takes 35 as its route instead of 0, which is closer to 38 though.

Some sensors are not listed in the topology because these sensors are isolated or unreachable sensors. When such a sensor wants to join the network, it will send a RREQ package. If some neighbor can serve as its route, it will reply a route. For instance, node 8 is an isolated sensor. When it wants to communicate with other sensors, it will send a RREQ package. In our experiment, sensors 0,1,5,7,14 and 24 all reply RREP back. Randomly, sensor 8 first receives RREP from node 7 so takes it as the route. In future development, we will check the power level of received RREP to choose the closest sensor in addition to the resources of replying sensors.

Table 1. Topology result by ROP

Cluster Heads	Cluster Members	
LRC 39	2 12 13 20 25	30 32 33
LRC 38	0 1 5 7 24	35 36
LRC 37	3 15 19	29 34
MRC 36		28
MRC 35	6 14	
MRC 32	10 16	
MRC 30	21 22	
MRC 29	23	
MRC 28	18 26	

As a comparison of our topology to existing routing protocols, several data packages are sent from node 18 to 38. In our topology, the route is from 18 to 28 to 36 then to 38. Ad hoc On-Demand Distance Vector Routing (AODV) [4], which is a well-known routing protocol, takes a route from 18 to 17 to 39 then to 38. We can see that the route of ROP is better than that of AODV, because it takes advantage of powerful sensors, rather than exhausting the resources of more resource-constrained sensors (sensor 17 in the case of AODV protocol).

6. Related work

According to its topology, a sensor network can be classified as a flat or hierarchical network. In a flat sensor network, sensors have similar roles in fulfilling tasks. Dynamic Source Routing (DSR) [5] and AODV [4] are two typical protocols for ID-addressed network. Sensor Protocols for Information via Negotiation (SPIN) [6] and Directed Diffusion [7] are two for attribute-addressed networking. ID-addressed networks have sensors with unique IDs but attribute-addressed networks have sensors only offering attributes. These protocols are not appropriate in our applications in that physical heterogeneity of sensors have to be considered.

In contrast with flat networks, in hierarchical networks, sensors form a clustered structure, where cluster heads have more responsibility than other sensors in their clusters. LEACH (Low-Energy Adaptive Clustering Hierarchy) [8] is a clustering-based protocol that utilizes local coordination among nodes to rotate the role of being the cluster head, which aggregates and reports data to a remote base station of interest. Taking more responsibility, the cluster head consumes much more energy than an ordinary node. The protocol guarantees that every node has equal chance to be a cluster head. In our applications, ROP ensures sensors take tasks based on their resources.

The Level Advertisement Clustering Protocol [9] is another clustering protocol focused on localized formation of hierarchical topology. Each sensor is associated with a particular level corresponding to a radius. The radius specifies the number of physical hops a sensor's advertisement message will travel. The algorithm takes the energy reserve of sensors into consideration and keeps topology change locally. Nevertheless, it requires periodic messages from all the sensors, which can result in wasted energy.

Fisheye State Routing (FSR) [10] introduces a multi-level fisheye scope so that routing updates are carried out more frequently in closer scope. Since periodic update of routing information is an unacceptable overhead for large-scale ad hoc networks, this protocol tries to maintain precise routing information for close neighbors but coarser information for remote sensors. As an extension, the Landmark Routing Protocol (LANMAR) [11] is a later development of FSR that utilizes landmarks for each cluster of sensors. Within a cluster, FSR algorithm is used. In contrast with FSR, which updates routing tables with a lower frequency for remote fisheye scope, LANMAR broadcasts routing updates among landmarks with the same frequency as within a cluster. To reduce overhead, landmark nodes summarize route updates before sending them to remote groups. Landmarks in LANMAR are like LRCs in ROP in terms of their communication role, whereas, ROP assigns significant role to LRCs in topology building. Furthermore, ROP selects cluster heads based on the resources of the sensors.

7. Conclusion

In this paper, we describe a network model that is adaptively formed according to the resources of its members. A protocol we named Resource Oriented Protocol (ROP) was developed to create the network model. This protocol entails two phases: topology formation and topology update.

In the topology formation phase, first, sensors report their characteristics of available resources, and then local cluster heads aggregate these reports and send to sensors with largest resource capacity (LRC). After this step, based on the reports, LRCs decide the topology and appoint cluster heads from the top to bottom levels. In the topology update phase, sensors maintain their route cache reactively. We stress in ROP that energy efficiency cannot always result in longer system lifetime especially in heterogeneous networks. Instead, balancing resources among sensors and saving energy for those more resource-constrained sensors are greatly helpful in lengthening the overall system lifetime.

The simulation results in GlomoSim show that ROP can build the topology of a heterogeneous sensor network efficiently and the routes based upon the topology are quite appropriate for balancing resources among sensors in the network.

In general, our Resource Oriented Protocol has several unique characteristics. First, network topology is based on the resources of its member sensors. Sensors with larger resource capacity have more communication and computational workload. Therefore, the lifetime of the whole network is lengthened by minimizing workload on battery-powered nodes. Second, several powerful sensors play the major role in defining network architecture and transferring messages, which once again saves limited resources of more energy-constrained sensors. Third, it considers the location and characteristics of mobility. Only in clusters whose members have moved will change structure. Finally, since the model takes resources of each sensor into consideration, a security model designed for heterogeneous sensor networks can easily fit into this architecture. Such a security model suited for resource constrained sensor network is our future research direction. We aim to enhance such sensor networks to vastly improve data privacy and security. The targeted areas of applications include tele-health applications, health care facilities and other care settings, in addition to more secure automation applications.

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