Sparsely Distributed, Mobile WSN Protocol

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Introduction

When electronic sensors find their way into hard-to-reach places, traditional wireless sensor network (WSN) protocols do not apply. Hard-to-reach places are classified as places in which it is difficult to deploy sensors, such as underground. This means that dense networks cannot be assumed and traditional WSN approaches will fail. Since these places are so remote, network lifetime must be extended even longer.

This project focuses on those networks which are sparse enough that sensor nodes cannot communicate with each other and must be deployed for an extended amount of time. It is also assumed that a mobile node can communicate with these deployed, stationary nodes. The final assumption is that the environment that needs to be monitored changes slowly; that is data is not so time critical that the travel latency of mobile node will be an issue, and 'old' data is not needed thus stationary nodes need not buffer much data.

Figure 1 shows a basic realization of the project:

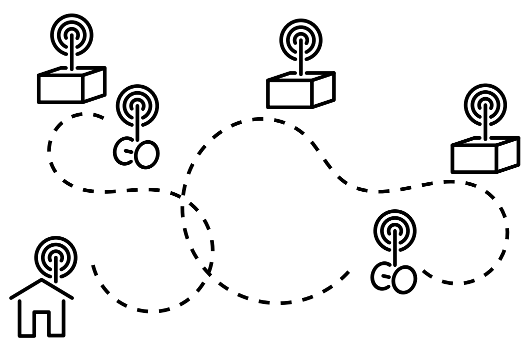

Figure 1: Mobile WSN nodes travel around to remote and stationary sensors to collect data and relay that data back to a base station.

A target application for this protocol would be irrigation where underground sensors would monitor the soil moisture. Earth does not allow for wireless communication over a few meters, thus above-ground, mobile nodes will need to move in range of underground nodes to pick up soil data. Soil data from the previous day (or older) is not useful for irrigation and the weather does not change so quickly that a field could not be queried before deciding to irrigate or not. Since the nodes must be buried underground, their batteries cannot be changed. While burying nodes takes a decent amount of effort, it is far less than running cable to connect these nodes, so a wireless approach is most appropriate.

The rest of the paper is organized as follows:

Related Work summary of similar work in this field

Project Description a high level description of how this protocol is implemented

Project Details a detailed description of the project's implementation

Experiment Setup how this protocol was verified and evaluated

Results the results of the experiments and demonstration

Bibliography

Appendix Glossary of commonly used terms

Related work

Mobile wireless networks have been around since the dawn of computing when data needed to be shared between two places not physically connected. Ad-hoc networks replaced floppy discs and hard drives with wireless signals and now sparsely distributed wireless sensor networks must rely on a limited power supply while still sharing their information.

Data MULEs (mules) were introduced by [3] as a means of collecting data from remote, stationary nodes and relaying that data to one or more central locations, thus forming a tiered network. These mules would randomly roam the environment. When a mule was in communication range of a stationary node, it would take data from that node and buffer it. When a mule came into contact with a sink node, it would dump its buffered data to the sink to be processed (or communicated via the Internet to be processed elsewhere).

Random roaming cannot give a quality of service guarantee, namely bounded message latency. [4] addresses the data mule scheduling problem using global location knowledge to find a near-optimal (quickest) path through the network. Many of the practicalities are ignored in this protocol, namely how a stationary node knows a mobile node is in range. It is assumed that only one mule exists (or the network is partitioned such that mules do not communicate with each other).

Dense networks provide additional communication possibilities. [2] expects stationary nodes to form multi-hop clusters so that a mule does not have to be in range of all nodes to gather data from all nodes. Here a premium is placed on speed and density, while network lifetime takes a backseat (as compared to other WSN protocols), though the protocol addresses all issues, including how mobile nodes are to alert stationary nodes of their presence.

[1] illustrates the benefits of radio-supported low power listening. Using minimal power, a radio will sense the channel for activity but is unable to interpret messages. Upon sensing activity, the radio can be fully woken up to interpret the signals and receive and send messages. Sensing power as low as $10\mu W$ to $1\mu W$ is proposed (based on the radio hardware).

Sensor Networks with Mobile Agents (SENMA) is proposed by [5]. SENMA's goals mirror that of this project, agreeing that maintaining a wireless network poses a large energy overhead on energy-limited nodes. Differences between SENMA and what we propose include the fact that the network will be sparse and latency guarantees will be attempted by the protocol. Much of the practical implantation issues have been ignored in SENMA, whereas this project shows functionality in a real demonstration.

Project Description

To accomplish data gathering in this sparse network, the protocol proposes three types of nodes:

- Stationary
- Mobile (data mule)
- Sink

The protocol will focus on the routing layer (of the network protocol) used by the mobile nodes. The protocol will have two largely distinct parts: a mobile to mobile routing protocol used to send event data between mobile nodes and eventually route packets back to the sink, and a stationary to mobile protocol used to ensure the delivery of event data from the stationary nodes when requested.

Stationary nodes will use as little energy as possible and are placed in hard-to-reach areas. They should sleep (stay in lowest power mode) as often as possible, only waking up long enough to check for mobile nodes.

Mobile nodes (or mules) will use as much energy as needed (as they can be recharged easily) and will roam the environment sending out 'wake-up' packets to let stationary nodes know they should share their data. Their paths may or may not take them in range of a sink, thus multi-hop inter-mobile node communication is needed. Mobile nodes will be location aware.

Sink nodes collect data from mobile nodes. It is possible to combine the mobile and sink functionalities, such as a mobile node being attached to a sprinkler in the irrigation example. The sink could also request (query) event data. Mobile nodes will be aware of these queries and work toward gathering event information for the specified event area (see Variations Section).

The mobile nodes will be used to obtain event data from stationary nodes in out of reach places, such as areas where the node density is too low to provide consistent and reliable inter-node communication. The protocol assumes that the data is not time-sensitive with respect to network latency and that old data collected from the stationary nodes can be safely discarded (as would be the potential case with soil analysis – only the most recent data is required to determine, for instance, the required water amounts).

Because the protocol is event driven, the mobile nodes need to have some geographical awareness. On-board GPS could be used in applications to obtain spatial knowledge of mobile nodes (and stationary nodes if the situation permits), but because it's fairly cost prohibitive and our demonstration will be indoors, 'region' nodes will be used in its place.

These region nodes will be distributed around the demonstration area fairly evenly, and will broadcast a packet with a region ID to the mobile nodes to simulate GPS functionality.

Project Details

Stationary-Stationary Protocol

Because of the space and node density constraints inherent in this project's assumptions (relatively small number of available nodes in any area), stationary to stationary routing and communication would not be feasible as it would require large amounts of energy to keep the network connected.

However, in some applications where a large, dense network was used as opposed to a small, sparse one, stationary to stationary could potentially provide significant energy savings as seen in [2]. By using a spatial correlation based MAC protocol, such as CC-MAC [6], individual nodes could effectively remain inactive for large durations of time while randomly selected representative nodes undertake the majority of stationary to mobile communication. This works especially well in an event based network where regions are of higher interest than specific nodes. Certain measures would likely have to be taken to ensure that selected representative nodes could communicate reliably with mobile nodes, but the details of the implementation are out of the scope of this project.

Mobile-Stationary Protocol

The mobile to stationary protocol attempts to minimize the energy consumed by stationary nodes by limiting the amount of time they spend "awake" when they are not needed, and by sending packets only when absolutely necessary. Each stationary node wakes up periodically for a set amount of time (100 ms in our demonstration). The sleep duration is set to a base value (30 seconds in our demonstration), but can be extended if communication with a mobile node recently occurred (as communicating with a mobile node again within that time frame is unlikely or unnecessary). This normal sleep time should be the maximum amount of time a mobile node would wait for a stationary node to wake up. A longer period would extend the network life, but as the duty cycle reaches 0%, the sleep time dominates the energy consumption.

During each waking period, the stationary node listens for a "wake-up packet" sent by a mobile node. The wake-up packet will indicate if data is in response to a query or otherwise. If the stationary node hears this, a data packet is sent to the mobile. Here it is assumed that the data packets will be small; if large data packets are used, a handshake protocol may be used to establish extended communication (see Variations Section).

After speaking with a mobile node, stationary nodes will sleep for an extended period of time (since the environment changes slowly, the mobile node needs time to move away from the stationary node and to save stationary node power).

Mobile nodes will wait for the full sleep duration interval at each stationary node they are sent to to ensure they will receive the intended data.

Mobile-Mobile Routing Protocol

It has been assumed that the energy consumption of mobile nodes is not a limiting factor in design decisions. A medium access control (MAC) protocol is needed, but the standard implementation will do. A routing protocol, however, must be developed which adapts to the sparse and mobile network.

Every (location aware) mobile node will keep track of the following values:

- Hops from sink count
- Reachable area (see Variations Section)
- Appointment book

Each value will be updated dynamically to account for major network changes (nodes failing, trees falling in the way, etc). Figure 2 illustrates these values.

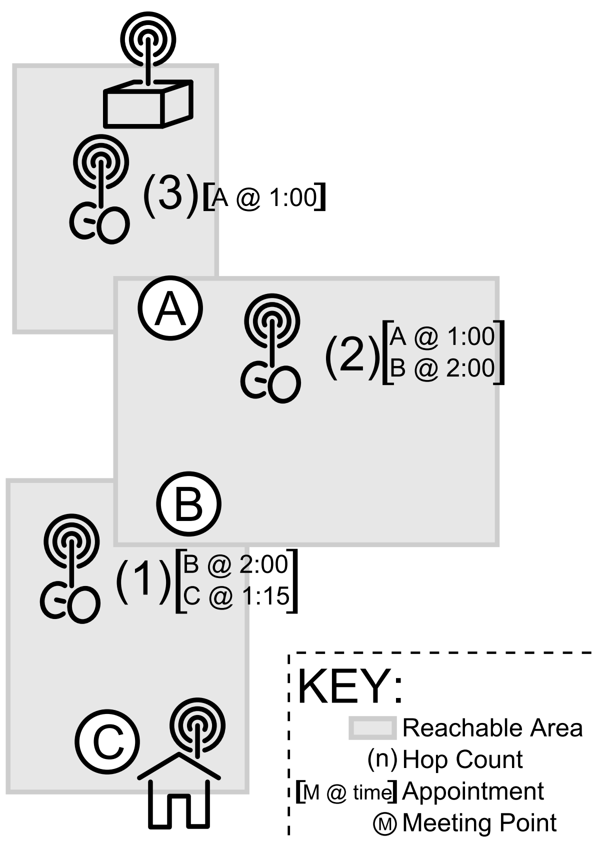

Figure 2: A visual representation of the mobile nodes' states.

Hops from sink count keeps tracks of how many mobile nodes must be communicated with to relay data to the sink. Mobile nodes who regularly come in range of the sink have a hop count of 1. When two mobile nodes meet each other, the one with a higher hop count takes the other nodes hop count + 1 and combines it with its own (using the moving average). Initially hop counts are unknown.

Reachable area: As a mobile node moves, it remember the bounds on its movement area. As time goes on, the bounds not visited recently shrink. As the mobile node moves into new areas, this range is extended in the direction of movement. This is only useful for querying the network (see Variations Section).

An appointment book is kept with a log of when and where to meet other nodes. When two nodes meet each other, they will schedule another meeting at the same place X time units later (2 minutes in the demonstration). This way, an upper bound can be placed on the latency (with respect to the number of hops a message must travel). If an appointment is missed, a node should not try to meet up again. Initially, the appointment book is empty, mobile nodes starting near the sink would gain an appointment with the sink right away. Though not implemented, a mobile node could make an appointment with a stationary node.

Mobile nodes must accomplish two tasks: forward source initiated data to the sink and retrieve sink-queued data. The values listed above accomplish this task. Mobile nodes move randomly, except when moving to appointments from the sink that they can satisfy (if they can reach the event area).

When a mobile node receives data from a source it must either relay that data to the sink or travel to the sink itself. If the nodes hop count is 1, it should wait until its next appointment with the sink to drop off data. If its hop count is more than one, it should wait until its next appointment with another node that has a hop count less than its own.

When two nodes meet to relay messages, the node with a smaller hop count should take these messages.

The movement of the mobile node is not specified as part of the protocol except for the following commands:

- Stop
- Wonder
- Go to appointment in X seconds

When the mobile node needs to communicate, it will tell the driver to stop. When communication is done, the node may wander. It will continuously send out signals indicating how long until the next appointment; it is the driver's responsibility to see that the mobile node arrives at the appointment on time. With respect to locating the location of stationary nodes, see the variations section.

Mobile nodes know they are in range of other mobile nodes because they can hear each others' wake-up messages. When a wake-up message is overheard, the hearing mobile node starts to transmit 'hello' packets (usually the channel works best in one direction, so the hello packet is repeated until the other mobile node responds). The hello packets indicate node IDs as well as hop-count-to-sink information which can be used to figure out if a node would like to move, copy its data to the other node, or keep its data. When the other mobile node responds with a hello packet, they exchange data messages. After a node transmits all of its data packets (if there are any) it sends an appointment message telling the other node when it would like to meet. A node must respond by confirming or sending another appointment message (if the offered appointment is not possible). After they confirm this, each will transmit wake-up messages with an invalid ID so as to not try to communicate with each other again, until getting out of range of each other (but still able to let stationary nodes know they are available to collect data). A similar approach is used by mobile-to-sink communication, though the sink does not keep appointments (it is assumed to be stationary).

Implementation Variations and Assumptions

Some assumptions have been made to simplify the protocol. Queries will not be implemented as it is assumed that mobile nodes will not act differently based on whether they have a query or not. If implemented, when data is queried from the sink it is first given to a mobile node. The query has coordinate information specifying where the data should come from (an area where stationary nodes exist). When two mobile nodes meet, the one whose reachable area is closest to the source should take the query. If a node has a query and it is in the target area, it should start to collect data messages. This also means that the reachable areas are not needed for the demonstration (though the mobile node is responsible for tagging its data with the location at which it was received).

End-to-end acknowledgments are also not included in the protocol (transport layer). It is assumed that mobile nodes will be fairly reliable and that packets will not be dropped, nor will congestion occur.

Data from stationary nodes will always be completely transmitted (to mobile nodes) or not at all. It is assumed that data reports are relatively small, thus they can always be transmitted rather than making decisions about which parts need to be transmitted. If large amounts of data were to be shared, it may be worth while to have some kind of handshaking between the mobile and stationary nodes.

Stationary node locations are found by 'wandering'. If a network is dense enough, random wandering may be enough. If this is not the case, stationary node locations could be pre-programmed into each mobile node, or – alternatively – there could be a setup period where a mobile node would explore its area, marking the location of stationary nodes.

Experiment Setup

Stationary power usage

Stationary power usage should be kept to a minimum as they will be located in remote, unreachable locations (such as underground). The power consumed by the environmental sensors of the stationary nodes is assumed to be negligible. This is realistic due to the very low duty cycle operation and the fact that the power required for radio communication is much higher than power required for sensing.

The motes must wake up once every X seconds to check and sense if a mobile node is around, where X is the number seconds a mobile node can/will wait for a response. The sense used to detect a mobile node should use the smallest amount of power possible. After a mobile node is sensed, the normal radio can be started and traditional communication would take place.

Two senses were tested for power efficiency: audio and radio. The microphone on the MTS310 sensor board was used along with its tone detection circuitry. The radio on the MicaZ was used with its power set to 3 (a minimum needed to reach three feet).

A duty cycle operation was used to test the power consumption of these two methods. 10% duty was used with an awake time of 3 seconds. The experiment was carried out for five minutes, and a mobile node was NOT in the area when this test took place.

The first tests showed that audio was less efficient, so multiple radio schemes were tested, including using the TinyOS low power listening and manually turning the radio on and off at very low duty cycles.

Network Topology

The stationary nodes were distributed throughout the entrance area of the Schorr center. The transmission power on each node will be reduced to simulate a larger network area. 7 stationary nodes will be used in the experiment, as well as 3 mobile nodes that will roam between each stationary node to facilitate network communication with the sink and a few 'region' nodes that simulate GPS-esque location awareness. Figure 3 shows this.

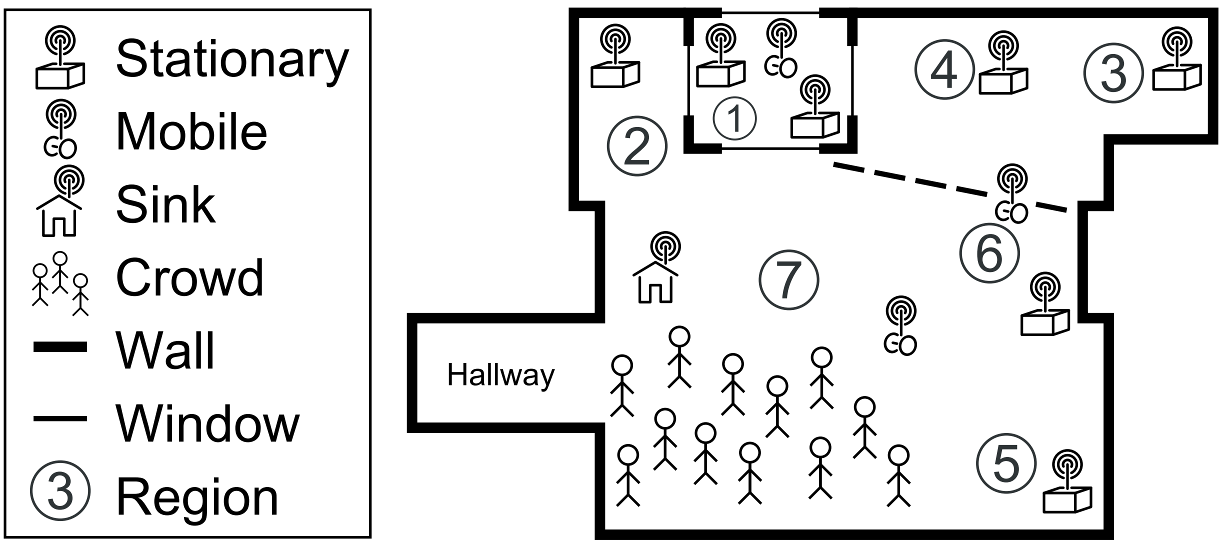

Figure 3: Network topology of the demonstration. 3 mobile nodes and 7 stationary nodes are used in an area with 7 regions.

One of the mobile nodes (topmost in Figure 3) is confined to the entry way (between the inner and outer doors), the leftmost node can only move along a straight line while the third (center) mobile node can move freely inside of the room.

Network Latency

The time period that mobile nodes use to schedule appointments determines the latency of the network as well as the feasibility of making these appointments. As long as mobile nodes can travel quick enough to gather data and meet their appointments, the network will stay connected and the latency will be bounded. To test for network latency, appointments were scheduled every two minutes using the topology described above.

The latency of a message sent from a mobile node can be expressed as follows:

$$L = \sum_{h=1}^{H} T_A \cdot (1 + \varepsilon_h)$$

where H is the number of hops (mobile relay nodes) between it and the sink; T_A is the appointment scheduling period and ε_h h is the packet error rate at a given hop.

The variance of the latency of the network is directly related to the variance of the packet error rate in mobile-to-mobile and mobile-to-sink communication. If the wireless channel remains consistent between transmissions, then the network latency should have a low variance. In turn, if the wireless channel is highly dynamic, the network latency will have a high variance.

Network Reliability

Mobile nodes pick up packets as they wander and exchange them as they come in contact with each other. As they do this, they mark how many they have. The number of them dropped in the exchange indicate the reliability of the network.

Network Throughput

Throughput will not been tested. Enough mobile nodes are needed to detect all the desired events. Since the number of mobile nodes does not affect this part of the protocol, it will not be tested.

Demonstration Setup

The demonstration will consist of seven stationary nodes, three mobile nodes, and seven 'region' nodes, using the topology reflected above. The mobile nodes need to be location aware to pull event data from areas. GPS is an unnecessary expense as the size of the demonstration area is relatively small (and indoors), so in its stead, the region nodes will be used to identify specific regions in the area. Each region node will have a unique ID that will be broadcast at a limited strength to try and limit the amount of overlap between regions. In the case of overlap, packets with a larger received signal strength will be used.

One of the advantages of having a mobile routing protocol is the ability to include nodes that would otherwise be out of communication range with other nodes. To demonstrate this capability, one of the motes will be located on the opposite side of the glass doors at the entrance to Schorr (to serve as a visually obvious indicator of obstruction, rather than simply lowering the TX power of each). Another mote will be placed off the ground, accessible only to a 'ghost' mobile node capable of reaching the higher node (which moves along a suspended string).

The mobile nodes will retrieve event data from specific regions of the network. As they collect the data, each mobile node will, at some point, communicate with another, designate a meeting place, and set an appointment to meet again and exchange event data.

The actions of the mobile nodes will be tracked with the on-board LEDs and 'loud' messages (messages indicating the state of each mobile node transmitted at high power), and the mobile nodes will be attached to remote control cars. When a mobile node needs to communicate, its red LED will be turned on indicating that the car should stop. When it is done communicating, the green LED will turn on (and the red will turn off) indicating that the car can move. The last LED will flash to indicate how much time is left until the next appoint, the faster it blinks, the closer to the appoint time it is. When it stops blinking (and is on), that means the car should be at the appointment location.

After the appointment (or timeout), this blue LED will turn off, then it will blink slowly, indicating the time until the next appointment. Should a mobile node have two meeting times, the LEDs will indicate only the next meeting while the second countdown is silently updated and displayed once the first is completed. Two PC applications will show this as well. The colorful map application will update showing which region each mobile node is in and in which regions mobile nodes have appointments (and how much time a mobile node has to reach these appointments). The text-only application also indicates the state of each mobile node and how many data packets are in its buffer.

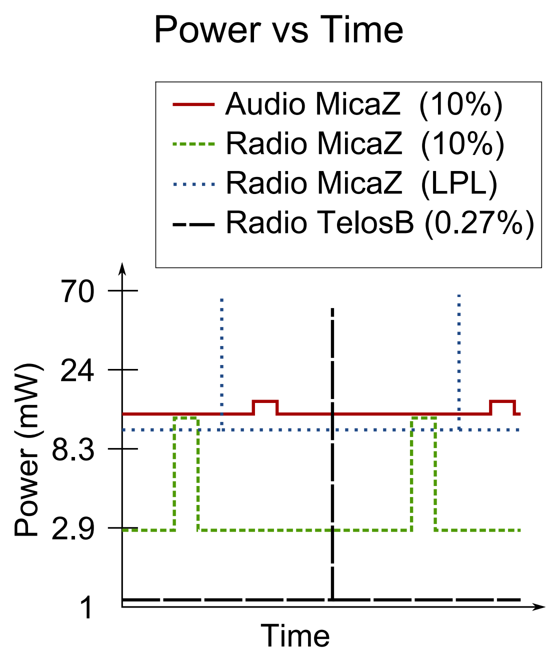

Figure 4: Power consumption of stationary using the microphone amplifier (audio) and of using the radio (transmit power = 3).

Project Results

Protocol Experiments

Stationary power usage

Figure 4 shows the average power consumption for audio and multiple radio schemes.

It can be seen that the microphone amplifier and tone detector use more energy than the radio. It is peculiar that the sleep time energy of the audio version is higher than the sleep time energy of the radio; this could be due to power used by the MTS310 sensor board. Thus the radio will be used to sense if mobile units are in communication range.

After choosing the radio, multiple variables had yet to be set: duty cycle and and low power listening. [Guo01] claims that using low power listening to sense activity on a channel (but not to decode the data) would require less power. CC2420 radios with TinyOS were used to implement the lower power listening, but the sleep energy savings were lacking. Here, very low duty cycles will be used, so the sleep power consumption must be optimized.

It was determined that being awake for 100 ms was enough to sense the wireless channel. A low duty cycle mode was tested using both MicaZ and TelosB motes. The results were not completely conclusive, giving factor of 5 power ranges for MicaZ motes and factor of 2 power ranges for the TelosBs.

The power levels that were reached (on average) with the TelosB motes yielded power usage of around 56 mW during awake periods and 1.2 mW during sleep periods. This would give a mote (powered by two AA batteries) a lifetime of around a year. At such a low duty cycle (under 0.5%) the awake energy does not factor in to the equation much, so a sleep time of 30 seconds will work well (though can be extended for a little more savings).

A third detection scheme is touch. This would be an optimal solution as a button could be attached to a hardware interrupt allowing a mote to stay in a deep sleep (or off), using a minimal amount of power without waking up to check for a mobile node. However, a physical interrupt is not applicable to this project as nodes are assumed to not be easily reachable; if a mobile node could touch the stationary sensor, it could also just sense the data on its own (although this approach could be useful in cases where a backlog of event data was necessary for the application).

Other untested senses include magnetic, IR sensors and using a lower power RF transceiver (separate from the CC2420's low power listening mode).

Network Latency

Given the demonstration topology, appointment period of two minutes and the fact that a mobile node must wait (on average) 15 seconds at each stationary node, it was observed that latency guarantees could be met. Using only three nodes, not every region's data could be collected every two minutes, but could be every five or six minutes. Adding additional mobile nodes would make the network latency bounded to two minutes per hop (four minutes total for the given topology).

The maximum latency for data in the demonstration was:

$$L = \sum_{h=1}^{2} 120 seconds \cdot (1 + 0) = 4 minutes$$

since the errors were recovered between appointments and there was a maximum of two hops in the network.

Network Reliability

The network was reliable. If mobile nodes drops a packet or does not finish the communication protocol, all messages are retained. (This creates the possibility of duplicate packets). Using the low transmit power, the rate of dropped packets was fairly high (10% or so), but using a stronger signal would help.

Network Throughput

This was tested as it is implementation specific.

Demonstration Results

The demonstration proved successful. The 'free' node (the one not inside the doorway or attached to a string) was able to make and meet appointments to pick up data gathered by the other mobile nodes as well as gather its own data from the remaining stationary nodes.

Conclusion

This protocol matches applications where hard-to-reach, slow developing, events need to be monitored. The specifics of a two tiered, mobile network have been presented and shown to achieve the goals set out by the protocol: conserving the energy of stationary, hard-to-reach sensor nodes by using mobile nodes to connect the network with a certain bound on the latency of the network. The protocol was demonstrated to work. Variations of this protocol were discussed as well.

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Appendix

Table of Terms

Term	Definition
Mobile Node	A device that has the ability to physically move about the network and communicate with other nodes in the network that are within its communication range. It has some data storage capabilities which it can use to relay data from one node to another. This device has an unlimited amount of energy.
Stationary Node	A device that remains in the same physical position and collects information about the environment through the use of electronic sensors. It can store a limited amount of data and can communicate with other nodes within its communication range. This device has a limited amount of energy to be used throughout its lifetime (two AA batteries).
Region/Beacon Node	A device that has knowledge of it's physical location and periodically broadcasts this information to mobile nodes within its communication range. This device exists solely for the purpose of simulating localization awareness of the mobile nodes. This device has an unlimited amount of energy.
Sink	A device that communicates with mobile nodes within its communication range. This device is considered the final destination for all the information about the environment that is collected as part of the application. This device has an unlimited amount of energy.
Region message	A message sent by a region node to a mobile node that contains information about the region node's physical location. Wake-up message (or packet): A message broadcast from a mobile node to stationary nodes indicating that the stationary nodes should send data packets to the mobile node.
Data message	A message containing information about the environment that was originally generated at a stationary node. These messages can be sent from stationary to mobile nodes, from mobile to mobile nodes, and from mobile nodes to a sink.
Sleep period	Time that a stationary node spends with its radio off so that it cannot communicate with other nodes in the network.
Awake period	Time that a stationary node spends with its radio on so that it can receive wake-up messages from mobile nodes and send DATA messages to mobile nodes.