The University of Sydney

School of Electrical and Information Engineering

A Cross-Layered Design Approach to Geographic Routing In Wireless Sensor Networks: Improving Efficiency Through Physical Layer Management

Author:
Daniel Babekuhl

Supervisor:
Zihuai Lin

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Contents

1 Abstract

This report outlines the development and simulation of a cross-layer design approach to improving efficiency via transmission strength adjustment in wireless sensor networks. It proposes a network layer protocol in which nodes are identifiable by their GPS location, and further, a type of 'minimax' routing algorithm with simple parameters that may be simulated and pre-set before node deployment for optimum network efficiency. Finally an approach to physical layer management is proposed, in which broadcast strength is adjusted based on neighbouring node locations. This provides a method through which power use can be fine-tuned in real-time by the network itself, in order to extend the lifetime of the network as much as possible.

2 Introduction

Of paramount concern with wireless sensor networks (WSNs) is power consumption [**?**]. This single metric affects almost all design features, because of the unusual nature of wireless sensor use-cases. This include:

- Battery-powered network nodes with no access to recharging
- Non-deterministic placement of network nodes (eg aerial drop)
- Deployment in difficult to access terrain
- Low data rate/relatively infrequent transmission (sometimes)
- Self-organising routing
- long-range transmission

For this reason standard networking models such as OSI and TCP/IP are often ill-suited to use in WSNs [**?**]. They are not designed for low power, nor are they designed to take advantage of low communication-rates where possible.

This report will outline an approach to cross-layer design in relatively large WSNs, geographically speaking. However the principles may be applied at all scales. It will begin by briefly providing an overview of cross-layer design, a concept that has been given much attention with regard to WSN design for some time. It will then explain the basic of receiver-based routing, also known as geographic routing.

It will then outline the design being proposed and explain the advantages it offers over existing geographical-based routing approaches. Finally it will present the results of a round of simulations aimed at demonstrating these benefits, and provide a WSN simulator that allows simulation of WSN parameters before deployment. This report then will close with suggestions of further research avenues to pursue.

3 Cross-Layer Design: A Brief Overview

Cross-layer design is a term used to describe departures from standard layered networking protocols: fundamentally, it describes a design in which some or all standard layers exchange or co-ordinate information to optimise network performance. While implementing some form of cross-layer design may seem like an obvious decision with regard to WSNs, in reality it is more nuanced as the design must improve efficiency on the whole. If, for example, it reduces computation but increases the need for stronger physical layer transmission, or results in less efficient routing protocols, the net affect of a localised improvement may negative.

For this reason architects of cross-layer designs must think holistically about the network, beyond the protocols of any single layer and even any single node. There is always the risk of unintended consequences, and it is highly consequential to design proposals that in many cases WSN nodes can not be replaced or updated after deployment. For this reason, while it is an exciting area of development with a plethora of idea already in existence, in practice some conservatism is often warranted, and a premium is often placed on cross-layer designs that do not stray too far from tried-and-tested solutions.

This is particularly true with regard to security of WSNs, which is a constantly evolving area in which standard approaches and protocols can become obsolete almost overnight.

4 Geographic Routing: How it Works

Geographic routing refers to routing protocols in which nodes exchange information about their geographical location. The simplest way to implement this is to equip nodes with GPS sensors, and allow them broadcast their location to other nodes. This is especially useful when the base-station's location can be hard-coded into sensor nodes before deployment: it means that each node can calculate its own and other nodes' distances from the base station and use that information to form an optimum routing path.

Geographic routing is often implemented along with some form of greedy algorithm - that is, and algorithm that proceeds by incrementally making the best choice from a small, immediate set of options. This process combined with location-aware nodes has been shown to produce impressive results with regard to emergent and robust WSN routing.

5 The Design Being Proposed: Utilising the Physical Layer

A logical step to take once nodes are locationally aware is to try to minimise unnecessary transmission, since is this one of the primary consumers of power in a WSN node. The approach being proposed in this paper is similar to standard location-based greedy approaches, with the addition of adjusting transmission strength of the physical layer in a more nuanced way, based on the received locations of the nearest nodes.

The algorithm can be described as follows:

1. Node i wishes to transmit data – it makes a low-power broadcast, including its GPS location, to the neighbors in its immediate vicinity and waits for replies. If it does not receive a reply, it increases its broadcast power in stages until it does.

2. The first time it does this it will start by covering default area A, however once it receives its first reply from a neighboring node n, it will store the GPS location of n and use it to determine the starting area A for any future broadcasts. This will ensure any future broadcasts are not wasted by being unnecessarily powerful or so weak that they don't reach any neighbors. Since nodes should not move very often, this should be an effective approach. Starting broadcast power will also be updated should the original n ever fail to respond, due to movement or failure.

3. Neighbors who receive the broadcast and are closer to the base station than node i will return their GPS location.

4. Node i broadcasts confirmation and data to node n located furthest away within its current broadcast range, at a power level based on node n's GPS distance. This recalibration of broadcast intensity again has the potential to save power, because if node n is located within in a close part of the broadcast area, full broadcast power for that area would be wasted. This is where the more nuanced physical layer management comes in: expansion stages are fine-tuned based on feedback about the surrounding nodes locations.

5. Upon receiving the data, node n repeats the procedure as the new node i until the base station is reached.

This 'minimax' approach (start with min broadcast power, select node max distance away within range) allows calibration between number of hops and broadcast distance for each node.

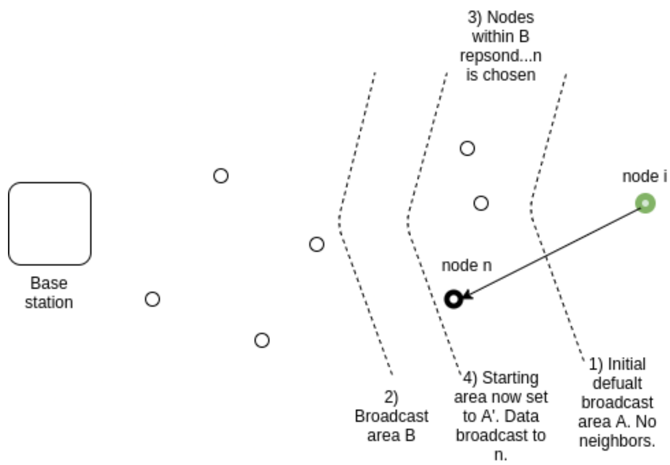

Figure 1: Location-based greedy approach with physical layer adjustment

6 Simulation of Routing Protocol

A simulator that executes a full routing operation of this cross-layer design has been especially built and is available here. It includes three user-definabe parameters:

- Number of Nodes.
- Area (edge length of a square area, in meters).
- Incremental broadcast area increase, in meters.

It then produces sixteen simulations. The steps of the simulation, once it is run, are as follows:

1. Randomly distribute nodes across assigned area.
2. select a random starting node, labeled the 'source node'.
3. Source node broadcasts a transmission request to a given starting area, consisting of its physical location.
4. nodes within the area broadcast their own locations.
5. Source node selects the node within the given area that is closest to the base-station, labelled 'server' in this simulation. This node is labeled the 'receiver node'.
6. The source node fine-tunes its broadcast strength to cover an area that spans 110% the distance of the receiver node, so that no power is wasted. It also stores this value as the starting point for its dext data transmission.
7. Source node then broadcasts the receiver node's location appended with the data message ('12345678' in this case).
8. All nodes who receive this message check to see if the location tagged at the start of it is referring to them. The receiver node realises that it has been selected as the node in the tranmission chain, and begins from step 3.
9. this process is continued until the server is reached.

As well as the visualisations of the WSN layout, there is also a plot of the some relevant distance metrics. These will be explained in the next section. A full log of all steps of the simulation are also displayed for more detailed review and confirmation of the process:

7 Results and Discussion

This simulation confirms that a nuanced adjusting of physical layer broadcast power based on node location, communicated via the network layer, does indeed reduce the total broadcast distance required. Below is are the layouts of 16 rounds of simulation:

```
 >> New Broadcast Node: [21733, 37952] <<
  Distance to server: 28188.61m

Node [21733, 37952]: sending broadcast request . . .
Broadcast distance: 6000m

(Idle nodes run.)


Node [21733, 37952]: sending broadcast request . . .
Broadcast distance: 9000m

(Idle nodes run.)


Node [21733, 37952]: sending broadcast request . . .
Broadcast distance: 12000m

(Idle nodes run.)

RECEIVER NODE SELECTED!:
 Location: [10575, 39602]
 Distance to server: 22272.61m away.
 Distance away: 11279.34m.
 New broadcast distance: 12407m

Node [21733, 37952]: data has been broadcast.

Node [10575, 39602]: package successfully received.

(Idle nodes run.)


 >> New Broadcast Node: [10575, 39602] <<
  Distance to server: 22272.61m
```

Figure 2: Sample log of one stage of one simulation

The orange square represents the base-station of the network. Below are the corresponding comparisons of three distance metrics for each simulation:

- Total unadjusted broadcast distance (blue). This would be the total broadcast distance had each node not revised its broadcast strength based on node location: that is, if it omitted step 6 from section 6, and incremented its broadcast power solely by predetermined stages.
- Total adjusted broadcast distance. This is the true total broadcast distance established by all nodes throughout the route.
- Actual routing distance. This is the actual total distance between the nodes in the route.

This simulation provides a strong indication that a more nuanced adjustment of broadcast power may have significant gains in efficiency over time. It also confirms that it is relatively insensitive to distribution of the nodes, and consistent across routes.

8 Further Steps

While this simulation is informative, it does not demonstrate another benefit of this design: the retention by nodes of their ’best-guess’ broadcasting power that is optimal for

```python
class Node:
  global single_sim_distances_unadj
  global single_sim_distances_adj
  global single_sim_route_distances

  def __init__(self, loc):
        self.location = loc
        self.dist_to_server = [0,0]
        self.broadcast_dist = power_increase
        self.receiver_node = ''
        self.nodes_in_range = []
        self.request_node_location = ''
        self.message = ''
        self.data = 0
        self.saved_broadcast_dist = 0

  # send location to any nodes in range
  def broadcast_request(self):
    print('\nNode %s: sending broadcast request . . .' % str(self.location))
    print('Broadcast distance: %dm' % self.broadcast_dist)
    for i in nodes:
      dist_node_i = get_distance(self.location, i.location)
      if (dist_node_i < self.broadcast_dist):
        i.request_node_location = self.location


  # scan for nodes requesting connection
  def scan_for_requests(self):
    # request received
    if self.request_node_location != '':
      # return own location
      for i in nodes:
        if i.location == self.request_node_location:
```

Figure 3: Sample code of part of a node class from the simulation

their neighbouring node, to be used as a starting point for all subsequent transmissions. This minimises future wasteful broadcasts that are either too weak to reach a node, or or more powerful than required. Should these gains also be factored in to the analysis I am confident this design would be shown to provide even further gains in power efficiency.

A further direction for expansion of this concept is potentially adjusting encoding schemes based on distance: that is, closer nodes needs less redundancy checks, and hence fewer bits broadcast. This could even be hardcoded as a lookup table within nodes, as opposed to requiring additional transmissions: for example, if a pair of nodes are x distance apart, use encoding scheme k.

And finally there is still room for optimisation of the parameters available for adjustment: namely, broadcast distance increments, and how closely to adjust broadcast distance once a neighbouring node's location is known. These are optimisation problems that may provide further gains

9 Conclusion

While there are many cross-layer designs in existence, it is still a fruitful area of research for wireless sensor networks because it has the ability to affect all aspects of their performance: power efficiency, data integrity, transmission delay, network lifetime, security, etc. There are some concerns about the risk of new designs having unintended consequences after deployment, however by innovating incrementally much more confidence can be put in each design and the net benefits it potentially offers.

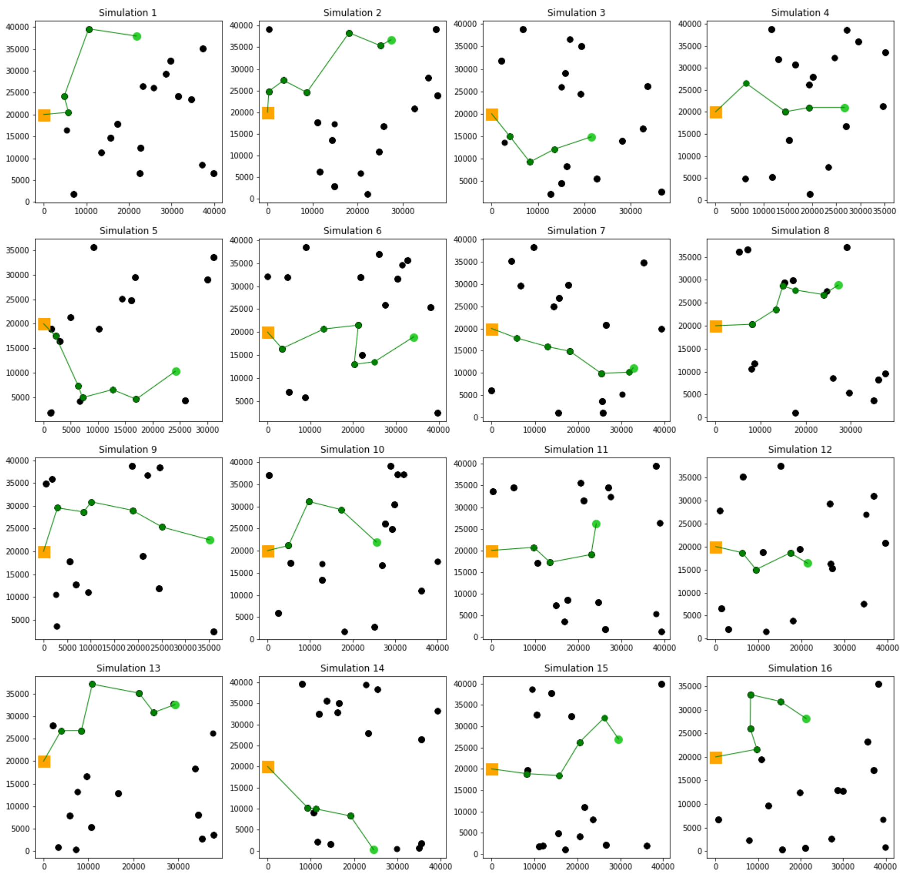

Figure 4: Random distribution of nodes for 16 rounds of routing simulation

Figure 5: Comparison of various distance metrics: it can be seen that nuanced adjusting of broadcast power based on node location reduces redundant broadcast distance in the route.