November 28, 2001

First Year Report

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Abstract

This first year report details the background, and motivation to the hypothesis : ”It is more efficient in terms of energy consumption to relay traffic through a set of nodes than to modify the transmission power [or move].”. Set out in this report are a series of experiments designed to test the hypothesis in a hostile environment where the collection of nodes have a collective task to carry out. The nodes are able to move and form an ad hoc network using low power radio devices.

Keywords

Low Power Radio, Ad hoc Networks, Energy Efficiency

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Contents

1 Background and Motivation **4**

2 Deficiencies in existing work **6**

2.1 Ad hoc Routing 6

2.1.1 Table Driven Protocols 6

2.1.2 Source Driven Protocols 7

2.1.3 Hybrid Protocols 7

2.1.4 Cluster-based Protocols 8

2.1.5 Power 8

2.1.6 Position 9

2.2 Sensor networks 9

2.3 Power aware / Power Saving 9

2.4 Simulation techniques 10

3 Hypothesis statement **12**

4 Testing the hypothesis **12**

4.1 Testing the hypothesis 1: 12

4.1.1 What is proposed 12

4.1.2 Why it is necessary to do this? 13

4.1.3 What assumptions will you make? 13

4.1.4 How do you propose to do the testing? 13

4.1.5 What results do you expect? 14

4.1.6 Time-scale 14

4.2 Testing the hypothesis 2: 14

4.2.1 What is proposed 14

4.2.2 Why it is necessary to do this? 14

4.2.3 What assumptions will you make? 14

4.2.4 How do you propose to do the testing? 14

4.2.5 What results do you expect? 14

4.2.6 Time-scale 14

4.3 Testing the hypothesis 3: 15
4.3.1 What is proposed 15
4.3.2 Why it is necessary to do this? 15
4.3.3 What assumptions will you make? 15
4.3.4 How do you propose to do the testing? 15
4.3.5 What results do you expect? 15
4.3.6 Time-scale 15
4.4 Why is the above set of work sufficient to test the hypothesis? 15

5 Appendix A - Literature Review 16

5.1 Ad hoc routing protocols 16
5.2 Table driven routing protocols 17
5.2.1 Destination Sequenced Distance Vector 17
5.2.2 The Wireless Routing Protocol 18
5.2.3 Source driven protcols 18
5.2.4 Dynamic Source Routing 18
5.2.5 Ad hoc On Demand Distance Vector 19
5.2.6 Temporally-Ordered Routing Algorithm 20
5.2.7 Associativity-Based Routing 20
5.2.8 Signal Stability Routing 20
5.3 Power Aware routing protocols 20
5.3.1 Power-aware Routing Optimization 21
5.3.2 Low-Energy Adaptive Clustering Hierarchy 21
5.4 Hybrid routing protocols 21
5.4.1 Zone Routing Protocol 21
5.5 Geographic routing protcols 21
5.5.1 Greedy Perimeter Stateless Routing 22
5.5.2 Location Aware Routing 22
5.5.3 Geography-informed Adaptive Fidelity 22
5.5.4 Fisheye State Routing 22
5.6 Cluster based protocols 22

5.7 Clusterhead Gateway Switch Routing 23
5.8 A brief comparison of ad hoc routing protocols 23
5.9 Multicast routing in ad hoc networks 23
5.9.1 AODV 23
5.10 Low Power Radio 23
5.10.1 IEEE 802 23
5.11 Simulators 25
5.11.1 NS 25
5.11.2 GlomoSim 25
5.11.3 OpNet 25

6 Appendix B - Timeline 26

7 Appendix C - Work so far 27
7.1 NS work 27
7.2 Literature review 27

8 Appendix D - Thesis Table of Contents 28

9 Appendix E - Possible scenario 30

10 References 31

1 Background and Motivation

This work has been funded by Philips and the EPSRC through an industrial case award; the work is being conducted in conjunction with the low power radio group at Philips Research Laboratories in Redhill.

The broad aim of this work is to examine issues in power consumption in ad hoc networks deployed in hostile environments.

Ad hoc networks are networks of autonomous nodes that have wireless connections between each other. Since there is no central point of connectivity such as a base station, such a system can only work if each node is prepared to forward packets destined for other nodes. Regrettably, since nodes move relative to one another, the precise connectivity of any given node is time varying. Put another way, the network topology varies as nodes change location, move out of range of other nodes or fail completely. In addition, either all nodes or a proportion of them are assumed to be self-powered. Consequently, the conservation of energy becomes important not just for the node concerned, but also for the survivability of the system as a whole.

This dynamic behaviour violates a set of assumptions that are made in the fixed network. Thus, for example, in the fixed network, hosts are assumed not to change their point of connection, allowing moderately static routing protocols to be deployed. This type of issue has to be addressed along with requirements that affect traditional routing protocols such as loop free routing, completeness and stability. There are several proposed solutions to this problem, such as DSR [35], AODV [57] and ZRP [23] to cite but three. However, it is worth noting that the field is very young and it is not possible to have particularly strong confidence in the performance of any of these solutions.

One major advantage of ad hoc networks, particularly from the viewpoint of military and civil defence applications, is the fact that the very dynamism that proves so troublesome in realising such systems forces them not to be reliant on single points of failure. As a consequence, there is no obvious point of attack or failure that would cause the system to cease operation. We believe that this also makes such systems highly suitable for use in hostile environments.

The original motivation for this work was cast in terms of space exploration by autonomous self-powered robots [8]. An example of a task that might be performed by such robots is the initial surveying of an area intended for colonisation, since the hazards are unknown and it maybe too costly to transport people and their support systems to carry out a surveying task. It was shown by the NASA Pathfinder mission [50] to Mars that remote control of a robot explorer is very limiting, since the round trip time for signals to Mars and back is significant. Using a single large device to carry out a task carries more risk than using a collection of small devices, since failure of a critical component on the large device will cause the mission to fail (e.g. the subsequent failure of the Mars Polar Lander [49]). In contrast, a collection of smaller autonomous devices that are able to cooperate to carry out a task may be more resilient to changes in the environment. Indeed, NASA have suggested precisely this approach for the exploration of asteroids [8].

In this environment, the self-powered robots have limited energy capacity, but a choice about how to use the energy they have. They may use it to communicate, move or perform the primary task that is the reason for their deployment. There are further variables:

- nodes may be able to turn off their receiver, thereby determining when they are able to receive incoming messages. In low power radio applications, the need to have the receiver continuously demodulating incoming signals in case a message arrives that is intended for this node can easily consume more power than transmission.
- nodes may be able to vary their transmit power. The energy consumption as a result of transmission is dominated by power amplification costs. It is not always necessary to transmit at full power when nodes are sufficiently close.

- nodes may have two entirely different power sources - one for movement (e.g. Hydazine N_2H_4 [1]) and one for communication/performance of the primary task, which will typically be electrical.
- the system is not necessarily homogeneous. For example, some nodes may have better energy reserves, faster recharge ability, or greater power consumption.

In tasks such as the exploration of Mars, the devices exploring the surface of the planet have a fixed amount of energy available to them at any one time. However, such devices also use solar cells to recharge themselves. This recharging is more effective in bright sunlight than in partial shade, so there is a further parameter in our scenario - the position of the node relative to the topography of the surface determines how fast it can regain energy and, consequently, its overall availability.

Work on energy saving has already been performed in the context of terrestrial mobile computing. The work proposed here is orthogonal to this - the techniques we propose to explore are complementary to standard techniques such as disk spin down, processor speed variation, and so forth. Of more direct influence is the work performed in energy efficient radio and protocol design for ad hoc networks. As a consequence, one assumption that we will make is that the system is architected around a low power radio system such as Bluetooth [29] , Zigbee [30] or 802.11 [28]. Given the availability of such systems, this assumption has the advantage that any work we do in simulation will be (partially) capable of validation in the real world.

Finally, it is worth noting that we believe that the lessons we are likely to learn from this work have application outside the rather esoteric application domain on which we based our scenarios above. Hostile environments are not confined to space - they exist in active volcanic environments, in Antarctic conditions, in earthquake zones and, regrettably, in buildings and tunnels at present. Appendix E explores the use of ad hoc networks in collapsed buildings.

[1] Although recent designs use both hydraine and electrical power to heat and accelerate to supersonic speeds [10]

2 Deficiencies in existing work

There is little specific work in this particular field - almost all work in terrestrial ad hoc networking has the premise that the nodes move independently of one another. In our situation, we have a control loop.

Within the networking literature, we believe that lessons may be learned from a number of fields:

- Ad hoc routing
- Power aware and power saving techniques
- Sensor networks

together with general work in simulation techniques, control theory and fuzzy logic.

2.1 Ad hoc Routing

The general goal in ad hoc networks is to provide connectivity between hosts with no fixed infrastructure. Unless no path exists between sender and receiver, i.e. the network is partitioned, then it is always possible to get a message from one host to another through aggressive flooding of the network. Ad hoc routing protocols are trying to achieve this aim more efficiently. However it is feasible that in very dynamic ad hoc networks that the only solution is to flood the network.

Given the postulated environment, it is clear that ad hoc routing protocols significantly underpin the foundations of the proposed work. Traditionally, ad hoc routing protocols have either reacted to changes in network topology as the occur or proactively disseminate topological information. Newer protocols use clustering techniques or have an awareness of power consumption or position or are hybrids of other ad hoc routing protocol classes. Each protocol has a different set of goals and priorities above and beyond those of providing a routing service in a dynamic, and thus demanding, environment.

2.1.1 Table Driven Protocols

Description
Table driven or *proactive* ad hoc routing protocols were amongst the first ad hoc routing protocols. There are two types of table driven protocol: link state and distance vector.

In link state protocols, each node maintains a view of the network topology with a cost associated with each link. Periodically, the node broadcasts the costs of its outgoing links, which ensures that the other nodes have a consistent view of the network. The updates cause each node to apply a shortest path algorithm to discover routes to all the nodes in the network.

In distance vector protocols, each node contains a "distance" for each node in its routing table , often the number of hops to the destination. Periodically, each node broadcasts a copy of its routing table to its neighbours. If nodes send stale information to each other, then distance vector protocols can be slow to converge. However, they do use less memory per node than link state protocols and have more localised updates. But it is still possible for an update to a distance to a node to propagate throughout the entire network. Distance vector protocols also suffer from a count-to-infinity problem, which can be addressed by techniques such as Poison Reverse or Split-Horizon.

Critique
In link state algorithms, nodes broadcast updates at different times. It is feasible that inconsistent information may be present in some routing tables and this can lead to short lived routing loops. Link state protocols suffer from the problem that in a highly dynamic environment, the amount of control traffic is

significant if all nodes are to achieve an identical view of the network. Recent protocols, such as STAR [55, chapter 4] and some cluster based algorithms, are designed to operate in a situation where not all nodes have a consistent view of the network.

The main limitation of distance vector ad hoc routing protocols is the periodic transmission of routing information that makes the network control traffic proportional to time rather than actual network traffic. In a highly dynamic network, distance vector protocols are too slow to adapt and converge once a change has occurred. In very highly dynamic networks they are unlikely to converge at all.

2.1.2 Source Driven Protocols

Description
Source initiated on-demand or *reactive* routing takes a different approach to table driven routing since routes are only created when a route to a destination is required. The source initiates a route discovery process and, when the process returns, an optimal route is chosen from the set of routes found. This route is established and maintained by a route maintenance process, until it is no longer required or the destination is inaccessible via every possible path.

Critique
Source driven protocols suffer from a scaling problem. If the average length of a path between two nodes is proportional to the diameter of the network, in hops, then, as the network gets wider (larger), the average path length gets longer. And since in source routing each data packet contains a list of the nodes that the packet must traverse in order to reach its destination, the number of bits transmitted due to the routing protocol increases. It is feasible that source routing could break down altogether if the number of bytes of routing protocol information is greater than the maximum packet size. This problem is soluble but it makes source routing more complex.

In very large highly dynamic networks the source route establishment process may be too expensive if the route is out dated before it is used sufficiently often to make the discovery process overhead a small fraction of the overall cost of the transmission. In this situation, directed flooding could produce improved performance.

Source routing techniques come into their own when used in small to medium sized networks where the mobility is moderate; indeed, this is a stated assumption of DSR. Source routing has a lower network overhead than broadcast-based routing techniques in this type of environment. This is due to nodes taking part only maintaining routing information for the communications they are involved in. Source routing protocols are less prone to suffer from routing loops and the slow convergence of routing tables found in table driven protocols. The information used to produce a source route is fresh because it has been generated on demand.

In very slowly changing networks, the overhead of having source routes in each packet reduces the throughput of the network, making source routed messages more expensive than table routed packets.

2.1.3 Hybrid Protocols

Description
Hybrid routing takes the best of proactive and reactive routing and combines the two. In hybrid routing each node maintains a zone around itself where it carries out proactive routing. The assumption is that inside a zone the network traffic is higher than outside the zone. So, if network control traffic is proportional to actual traffic, it is less efficient than having control traffic proportional to time, i.e. proactive routing. However where traffic is lighter, i.e. outside the zone, then network control traffic proportional to network traffic is more efficient having than control traffic proportional to time. Thus traffic inside the zone is routed

proactively and traffic outside the zone is routed reactively. To make hybrid routing efficient, the size of the zone must be able to dynamically adjust to changes in traffic patterns.

Critique
Hybrid protocols are susceptible to the problems of both table driven and source driven protocols if the zones are configured badly. Conversely, if configured correctly, many of the problems due to table and source driven protocols are reduced and the advantages exploited. Combining the two routing concepts is not without an extra management cost, and in ZRP this comes in the form of an additional protocol.

2.1.4 Cluster-based Protocols

Description
The use of clustering and hierarchical approaches to routing are valuable methods of breaking the problem down into manageable components for which tasks or sub-tasks can be allocated. The following set of work provide a good starting point for this approach, [44], [13] , [47] , [7] ,[54] and [59].

The intent of clustering is to group nodes into geographically close collections, which form peer-to-peer links for communication between nodes in the cluster. Each cluster has a gateway node(s) through which information destined for the outside the cluster must pass. In cluster based networks, routing is defined as occurring via clusters rather than via nodes. Each cluster is responsible for routing packets through itself.

Critique
Clustering solutions do not specifically address the energy consumption issues. The use of cluster gateways can impose additional overheads, when a node in a cluster is in a different cluster to near-by node with which it wishes to communicate, the communication must occur via the cluster gateways, rather than directly. Additionally clusters place an additional management overhead on the network.

However the positive side of clustering solutions is that they provide in path fault tolerance for end-to-end routing. For example, in a source based routing protocol, if a node moves, all the routes passing through that node must be recomputed by the source(s); in a cluster based protocol, only the path through the cluster must be recomputed.

2.1.5 Power

Description
One approach to reducing the energy consumption of ad hoc networks is to switch off the radio for a period of time and then switch it back on again. The following two pieces of work investigate this effect and demonstrate that the life span of the network can thereby be extended, [64] and [11]. The work, GAF, by Ya Xu et al. at USC/ISI, combines switching off the radio device with an adaptive fidelity algorithm for nodes in close proximity to each other. This approach could be taken further by having N-levels of power rather than binary power. Combining this with adaptive fidelity could provide additional energy savings.

The SPAN work of MIT is an energy-efficient algorithm to decide whether a node should form part of a backbone of ad hoc nodes which provides network connectivity. The nodes decide whether to join the backbone or not using a distributed algorithm. The algorithm used in SPAN is a possible candidate for deciding whether to modify the transmission power or to relay traffic via other nodes.

The work by Qun Li et al at Dartmouth [45] describes a routing protocol which aims to increase the lifetime of the entire system. This work is of interest to our proposed work although it does not take into account the ability for radio devices to modify their transmission power. However, one of the interesting aspects of the work is that the decision process is localized to clusters with each cluster being given the task of routing messages through themselves using the most efficient route.

Critique
The general problem with power aware routing protocols is that they assume that the radio devices can either be off or on, rather than being able to modify the transmission power. Some 802.11b chipsets allow the modification of the transmission power, but Zigbee [6] does not, since there are no applications that require it, a catch 22 situation.

2.1.6 Position

Description
Position-aware routing protocols use geographic information to aid routing. Having geographic information can reduce the amount of wasted network traffic by steering traffic towards its destination.

Critique
There are many position aware protocols but the main criticism of them is that they are reliant upon GPS data to provide positional information. However, it is possible to build relative topology maps by measuring round trip times to devices. GPRS is one example of a position aware routing protocol but it relies on GPS data which currently makes it impossible to use in an environment such as Mars. An alternative solution must be found.

Other than the additional cost of maintaining and obtaining the positional information of nodes in the network, geographic based protocols have few drawbacks other than the those already associated with the routing protocol family they use for the underlying structure. The main advantage of geographic routing protocols is that they direct traffic to only those relevant portions of the network.

2.2 Sensor networks

Background
The Smart Dust work at Berkeley is similar in concept to the proposed work, but takes a different approach of using ultra low powered devices that operate in a master slave arrangement using optical networking to communicate between the Smart Dust and a base station. The current Smart Dust device fits in a $1cm^3$ package, including a power supply of 1 Joule. The communication system of the Smart Dust is not well suited to providing ad hoc networking facilities. A situation that might be more feasible is for the Smart Dust base stations to provide ad hoc networking and act as a cluster head for communicating to and from the Smart Dust sensors. However, this is beyond the initial scope of this work since it introduces too much diversity into the system.

Critique
Much of the work on sensor networks examines ultra low power devices. Using and designing ultra low power devices incurs limitations not associated with the networks proposed here; for example, the sensors in Smart Dust are not able to act as routers for other sensors.

2.3 Power aware / Power Saving

To provide true low power devices energy saving needs to be carried out at all levels from applications to hardware. Although processor speeds are increasing at roughly Moore's law, battery lifespan is growing much more slowly; at roughly 20% every ten years. Various techniques can be employed to reduce energy consumption, some of which can be carried out independently; others require coordination of various components.

Disk spin down
To keep a hard disk spinning can be expensive if it is "idle". However, there is also a cost associated with spinning up a stationary hard disk to its operating speed. So a trade off needs to be made; is it more

efficient to keep a hard disk spinning “idle” or to spin down the hard disk and to spin it back up again when it is required, suffering an additional latency in disk access ? In fact, there is a minimum idle time for the disk for this to be more efficient. Since the hard disk is a slave device to the operating system and the applications it is difficult for the hard disk to predict when it should spin down and when it should keep spinning. If the operating system and the applications are power aware then disk access can be scheduled to provide optimal usage of the energy.

Processor stepping
Each processor cycle uses energy, so the higher the clock rate of a processor the faster it uses energy. If a processor is “idling” waiting for work to do it is wasting power. It can be more efficient to reduce the clock rate of the processor and take a longer period of time to carry out computations, thus leaving the processor to idle for less time. Intel’s mobile Pentium III processor use processor stepping technologies. But reducing clock speed is not the most efficient thing to do, since if the clock speed is linearly reduced, then the energy is linearly reduced, but execution time is linearly increased. This only provides a benefit if the idle time of the processor is decreased. A more effective solution is to reduce the voltage to reduce the clock speed at which the processor runs, since reducing the voltage by a factor of n decreases the energy usage by n^2 [25].

Load balancing
Load balancing is a technique in which tasks are shared out between a collection of devices, with the idea that the overall performance of the system in maximised according to some metric. This metric maybe the the response time of the application, in the case of battery powered nodes, the amount of power consumed, or some combination of metrics. To reduce the energy consumption of a mobile device, it may be more efficient to transfer some of the processing task that it would perform to a more powerful host. The transferring of the task is not without cost, and the savings in transferring the task to another host must outweigh the costs involved in the transfer.

Communications
Work by Robin Kravets, Karsten Schwan and Ken Calvert [42] examines power aware communications for mobile computers, looking at the entire picture rather than a specific a subset of the problem such as power usage of the radio device, CPU power consumption in generating the traffic. However, ad hoc communication strategies are explicitly not investigated in this piece of work. But the strategy taken in this work to evaluate the overall system rather than a specific subset is one we wish to follow. Earlier work by Robin Kravets and P. Krishnan [43] proposed a new protocol for controlling when nodes are active. A node, acting as a master, defines when the base station, acting as a slave, is able to transmit information to it. This allows the mobile station to suspend its radio device to conserve power. However, as the work points out, leaving the device suspended for too long causes significant latency in communications, whilst suspending for too short a period leads to energy wasteage. Hence it is proposed that the protocol be adaptive to the communications patterns of the system. But taking this a step further and exposing the MAC layer, layer 1 of the OSI model, to Application layer, layer 7, breaks the concept if layering but may be necessary if power aware applications are to be developed.

Gossip based networks maybe a possible technique for information and routing dissemination; these have not yet been investigated.

2.4 Simulation techniques

To make ad hoc networks interesting, a large number of mobile nodes are needed. But for practical and economic reasons it is infeasible to actually perform large scale experiments, so simulation becomes the method of experimentation. Real small-scale tests are viable and both provide an insight into some of the problems in developing and deploying a working system, and provide a method to validate the simulation.

The Monarch Project [21] used such a technique in [46]. The new Millennium bridge in London has shown that simulation does not provide a perfect representation of reality but rather an approximation that is limited by the information fed into it and the model used.

The simulation systems in use by the ad hoc network community are NS [22], Glomosim [20], the commercial simulator OpNet [32] and many custom simulators and mathematical analysis packages.

Work by Wei Ye et al. at USC and ISI [66] focused on the combining of two simulators NS [22] and Arena [2] to provide a simulation environment for a set of robots to explore and evaluate. The Arena simulator is designed to simulate the operation of the robot in terms of its movement and its sensors, and provide reasonable approximations to the operation of real systems. NS provides the simulation of the network component of the system. Socket style communications are used to link the two simulators so movement in Arena is relayed to NS, updating the radio propagation models to account for the movement. The work's aims were to evaluate the simulation system, which it showed to be feasible. However the work did not examine energy usage of the simulated system, but equally did not preclude it.

3 Hypothesis statement

”It is more efficient in terms of energy consumption to relay traffic through a set of nodes than to modify the transmission power [or move].”

Movement is an additional complication that would be an extension to the work.

The problem domain is a set of wireless nodes with lower power radio systems, that are able to modify their radio transmission power and, optionally, move. Initially, the environment will be assumed to be planar and uniform, later obstacles will be introduced.

4 Testing the hypothesis

The general scenario for the experiments is that the nodes in the network are collectively tasked to perform a series of tasks measurements, for example . To carry out a task the nodes must co-operate with each other and must move around the planar environment. In contributions 1 and 2 below, the movement of the nodes is for the sole purpose of carrying out the task. There is no intention to modify the movement of the node, including stopping and slowing of motion.

Testing the hypothesis is broken down into three components, with each component building on the lessons learnt in the previous component(s) whilst adding additional complexity to the problem. Briefly section 1 deals with a collection of homogeneous nodes, section 2 deals with heterogeneous nodes and section 3 deals with nodes that move to aid routing. Movement in sections 1 and 2 is related solely to the task being carried out by the nodes in the network, whereas, in experiment 3, movement to aid routing and movement related to the task are proposed.

4.1 Testing the hypothesis 1:

4.1.1 What is proposed

The overall aim of this sub-series of experiments is to examine the effect of modifying the transmission power of homogeneous ad hoc nodes in an obstacle free bounded planar environment. Initially, the work will focus on establishing a set of baselines for future experiments to be measured against. This will involve defining an experiment where all the events and parameters are known in advance and the communication strategy can be modified to provide an optimal or near optimal solution. The experiment will be repeated with decreasing degrees of foresight built in, and the nodes carrying out more extensive routing decisions based on a set of models. These may include :

- a pre-programmed sequence of actions triggered by certain events.
- learned behaviour
- clustering techniques

Topics of consideration will include the use of clustering techniques for the control of the system where the cluster heads control the communications, possibly make a reservation for a communications stream via cluster-heads. However, the exact form of this section of experiments will be defined during the experimental planning phase.

One component of the set of experiments in this section is the use of real devices to validate simulation parameters. If the use of real hardware is not feasible, then measured parameters provided by Philips will be used.

4.1.2 *Why it is necessary to do this?*

Tuning ad hoc nodes' radios to deliver power aware communications is an area in which little work has been carried out. The main reason behind the work defined in section 1 is to explore the application area through experimentation and analysis. The initial work is to be focused on setting a set of baselines and validating the system.

4.1.3 *What assumptions will you make?*

The following assumptions are being made.

- All the nodes are the same.
- Each node has the same finite amount of energy.
- Nodes have a random probablity of failing.
- All communications are known.
- Perfect radio communications occur.
- There are no obstacles on the planar surface and the nodes are point objects.
- Use a single radio model.
- Node movement is only related to the task being carrying out.
- The cost of node movement is not taken into account.

These assumptions are self-explanatory. However, the use of a single radio model maybe controversial since the ratio of the transmit power, receive power and idle power consumption of the radio could easily be highly influential in the results of the experiment. This needs to be taken into account when designing any model. The random probability of node failure is to simulate the nodes falling down holes, driving off cliffs or being hit by a meteor.

4.1.4 *How do you propose to do the testing?*

A large portion of the work will be carried out using simulation since it is difficult to use real devices for large networks. However, the simulations are less worthwhile if they are not validated against reality, thus it is proposed that a portion of this series of experiments is concerned with the validation of the simulation, using real hardware where possible. The simulator to be used is likely to be NS 2 [22], but Glomosim is being re-evaluated following recent releases of the software. Also the building of a custom simulator has not been ruled out.

The testing set up designed for this section needs to have extensibility built in, for example it needs to be possible to define heterogeneous nodes, with the worst-case scenario being that every node is different.

The following metrics will be used to evaluate the performance of the system system under different sets of conditions.

- Throughput (goodput) of the system.
- Time before x percent of nodes fail.
- Time to complete of task.

- Time before y percent of nodes are not connected.

The use of a database to manage the experiments is the expected approach that will be taken. The idea is to query the database to generate experimental test scripts and analysis scripts.

A significant problem in the simulation of ad hoc network is the amount of data generated, since a series experiments for each set of parameters are required to carry out variance reduction.

4.1.5 What results do you expect?

The expectation is that reducing the transmission power of the sender to produce smaller hops of communication will increase the lifetime of the system. The ratio of the transmission power to receive power will effect this statement significantly since if the cost of the reception outweighs the cost of transmission then it is expected that increasing the transmission power to have larger hops will be more efficient. However the addition of cross traffic will make it more efficient to have smaller hops taking advantage of a node which is already listening and relaying traffic.

4.1.6 Time-scale

The main core of the work in this section is expected to take 6 months. The breakdown of this section is further set out in Appendix B.

4.2 Testing the hypothesis 2:

4.2.1 What is proposed

The work proposed for the second main section of the work is to investigate the effect on the solutions discovered in section 1 using non-heterogeneous nodes.

4.2.2 Why it is necessary to do this?

The work in section 1 was intentionally very simple, this work is necessary to test the models and methods developed which have resulted from the experimentation in section 1 using heterogeneous nodes. In a real environment nodes are more likely to be heterogeneous than homogenous.

4.2.3 What assumptions will you make?

The assumptions of section 1 are still valid except that nodes are now heterogeneous rather than homogenous.

4.2.4 How do you propose to do the testing?

The testing of the second section is dependent upon the technique chosen for section 1.

4.2.5 What results do you expect?

The expected results are that the energy efficiency of the system will reduce since the heterogeneity of the network will effect the assumptions and optimisations that were made when the network was homogenous.

4.2.6 Time-scale

This section is expected to take approximately 6 months, Appendix B provides more detail of the breakdown of this section of experimentation.

4.3 *Testing the hypothesis 3:*

4.3.1 What is proposed

Section 3 is an extension of section 2, providing additional functionality to the nodes to be able to move to aid routing.

4.3.2 Why it is necessary to do this?

It is necessary to add movement to aid routing to investigate the second component of the hypothesis.

4.3.3 What assumptions will you make?

The assumptions in section 2 still hold, with the exception that the nodes are able to move to aid routing. Leading on from this changed assumption the dropping of the is assumption that the cost of node movement is now being considered.

4.3.4 How do you propose to do the testing?

The testing of the third section is dependent upon the technique chosen for section 1 and any modifications made in section 2.

4.3.5 What results do you expect?

I expect that moving to aid routing will reduce the chance of a network partition occurring, since nodes will be able to take pre-emptive action to prevent partitioning. However this preventive action isn't without a cost in terms of the cost of the physical movement and the additional management traffic required. There is a point where the overall cost is less than the savings achieved. Additionally if nodes are able to move to reduce "long" transmission distances, then the overall energy consumption will reduce.

4.3.6 Time-scale

The main core of the work in this section is expected to take 6 months. The break down of this section is further set out in Appendix B.

4.4 *Why is the above set of work sufficient to test the hypothesis?*

Section 1 addresses the broad concept of the hypothesis and aims to show that for a very specific set of variables that the hypothesis is true. By starting with a very structured environment, at least a component of which could be validated against reality, and proving, under certain conditions that the optimal solution to the problem is that it is more efficient to route using small network hops rather than long network hops. However using low power radio devices reverses the conventional model of radio power consumption in the different modes of communication, which effects the validity of the previous statement. The addition of cross-traffic to the system again modifies the energy consumption characteristics of the system. It is expected that a highly complex scenario will emerge. By iteratively making the environment less structured and closer to "reality" a more general testing of the hypothesis is achievable. Sections 2 and 3 diversify the structured environment of section 1.

5 Appendix A - Literature Review

5.1 Ad hoc routing protocols

Since the 1970s wireless networks have grown in popularity. Ad hoc networks are networks of autonomous nodes that have wireless connections between each other. These connections can created and destroyed, changing the network topology as nodes change location, move out of range of other nodes or fail completely. Ad hoc networks pose an additional set of problems to those encountered in traditional fixed networks or wireless cellular networks. Dynamically forming the communications infrastructure from mobile devices is the source of these complications. One way of thinking about this is to imagine the problems caused by continually moving and changing the router you use to get from your local subnet to the rest of the world. How would packets get to or from you ? This type of question has to be addressed along with requirements that affect traditional routing protocols such as loop free routing, completeness and stability. The proposed solutions to this problem have focused on developing ad hoc routing protocols such as DSDV [56], DSR [35] and AODV [57] to cite three.

In an ad hoc network each node can forward packets destined for other nodes. Nodes maybe be mobile and have fixed power levels which adds extra constraints to the network that is not present in fixed networks. Mobility of the network infrastructure may cause the network topology to change rapidly during the lifetime of the network, thus routing protocols for ad hoc networks must be able to adapt to the changing topologies.

In [55, page 17] Perkins discusses the policies nodes might adopt when transmitting, receiving and forwarding packets. A node that is energy constrained might take a different approach to participation in a global system to a node that is not energy constrained. Leaving aside security considerations and configuration issues, nodes in a fixed network that are powered are able to acts as routers for other nodes at little cost to themselves in terms of processing power [2]. However in an energy constrained ad hoc network, the additional constraint of a limited amount of energy requires nodes to be more cautious about what tasks they carryout themselves or on behalf of others. Tasks such as packet forwarding are expensive since they require reception, processing and transmission of packets. It can not be assumed that using the radio to transmit and receive packets is significantly more expensive than leaving a radio to idle. It is shown, respectively, in [61], [40] and [11] that the ratios for energy consumption for the different states idle:receive:transmit are 1:1.05:1.4, 1:2:2.5 and 1:1.2:1.7 (AT&T 802.11 PCMCIA card). Although these figures slightly differ, it does show that a radio in the idle state uses at least 50% of the energy of the receive state and at least 40% of the energy of the energy of the transmit state, hence it is not realistic to ignore the idle state. It is costly for a node to act as a forwarder for other nodes, since to remain in a listening state is expensive. In [65] it is shown that the energy consumption of the four ad hoc routing protocols AODV [57], DSR [35], DSDV [56] and TORA [5] are very similar when taking into account the idle energy usage of the nodes of the under the model proposed by [61]. This leads to approaches such as SPAN [11] and GAF [65] where the radios are turned off, rather than being left to idle, and awoken at intervals to listen for transmissions. Switching the radio off for periods of time causes an increase in network latency but increases the lifetime of the system. Other issues involved in ad hoc routing are set out by David B. Johnson in [34] and [36].

Since Elizabeth Royer and Chai-Keong Toh wrote "A Review of Current Routing Protocols for ad hoc Mobile Wireless Networks " [60] in 1999, ad hoc networks have made significant progress. Many new classes of protocol have been developed, expanding the two main classes considered in [60], namely Source driven and Table driven protocols, to a whole collection of more specific classes. These classes are Hybrid Protocols, Geographically Aware Protocols, Clustering Protocols, Locally Repairing Protocol and Energy Efficient Protocols. The categorisation of routing protocols in [60] placed a clear distinction between

[2] Assuming a moderate amount of packet forwarding. Although in an interrupt driven system, high levels of network activity can cause latency in the system, which is much higher than the processing requirements of the forwarded traffic would suggest.

Source driven and Table driven protocols. With the additional classes mentioned above, the distinction between protocols is not so clear. Protocols have properties of one or more classes or ad hoc protocol. For example ZRP [23] is a Hybrid protocol and has features of both Source and Table driven protocols. Activity within the IETF on ad hoc networking is co-ordinated by the MANET group [4].

The general goal in ad hoc networks is to provide connectivity between hosts with no fixed infrastructure. Unless there exists no path between sender and receiver, the network is partitioned, then it is always possible to get a message from one host to another through aggressive flooding of the network. All ad hoc routing protocols are trying to do, is to achieve this aim more efficiently in terms of a set of metrics. It is feasible that is very dynamic ad hoc networks that the only solution is to flood the network.

5.2 Table driven routing protocols

Table driven or pro-active ad hoc routing protocols were amongst the first ad hoc routing protocols. There are two types of table driven protocol, link state and distance vector.

In link state protocols each node maintains a view of the network topology with a cost associated with each link. Periodically the node broadcasts the costs of its outgoing links, which ensures that the other nodes have a consistent view of the network. The updates cause nodes to apply a shortest path algorithm to discover its routes to all the nodes in the network. Since nodes broadcast updates at different times it is feasible that inconsistent information maybe present in some routing tables and this can lead to short lived routing loops. Link state protocols suffer from the problem that in a highly dynamic environment the amount of control traffic is significant, if all nodes are to achieve an identical view of the network. Recent protocols STAR [55, Chapter 4] and some cluster based algorithm are designed to operate in a situation where not all nodes have a consistent view of the network.

In distant vector protocols each node contains in its routing table a metric for each node, often the number of hops to the destination. Periodically each node broadcasts a copy of its routing table to its neighbours. If nodes send stale information to each other, then distance vector protocols can be slow to converge. However they do use less memory per node than link state protocols and have more localised updates. But it is still possible for an update to the distance metric for to a node to propagate throughout the entire network. Distance vector protocols also suffer from a count to infinity problem that can be addressed by techniques such as Poison Reverse or Split-Horizon. DSDV is an example of a distance vector based ad hoc routing protocol. The main limitations of distance vector ad hoc routing protocols is the periodic transmission of routing information that makes the network control traffic proportional to time rather than actual network traffic. In a highly dynamic network distance vector protocols are too slow to adapt and converge once a change has occurred. CGSR and WRP are also distance vector protocols.

5.2.1 Destination Sequenced Distance Vector

Destination Sequenced Distance Vector, DSDV, was described in [56] and [55] section 3.3.

This is one of the first ad hoc routing protocols and is basically an adaptation of the Bellman Ford algorithm [38]. It was developed by Perkins et al. in 1994 and has been superseded by other ad hoc routing protocols, including AODV also by Perkins [1]. Each node maintains a list of all other nodes in the network along with a next hop to them, the number of hops to the destination and a sequence number. The sequence number is used to distinguish stale routes from fresh routes. Routing table updates are periodically broadcast throughout the network to ensure consistency. To minimise the effect of these broadcasts there are two different types of broadcast, a full update and a partial update.

One problem with DSDV is that it broadcasts routing table updates throughout the network, many of these changes may never be used by the hosts receiving them and hence are wasteful of bandwidth. Since DSDV is not source routed then the complete route to the destination is not required, so it is more efficient to locally correct a route failure as is the case in cluster based routing protocols.

5.2.2 The Wireless Routing Protocol

The Wireless Routing Protocol, WRP, is a table based routing protocol [48], where nodes inform their neighbours of updates messages, which must be acknowledged. A constant level of network activity must be maintained by the node either through it sending data or via *hello* messages. The interesting component of WRP is that it ensures loop free behaviour by nodes communicating the distance to the destination and the second to last hop of each route. Each node is then forced to perform consistency checks of predecessor information reported by all its neighbours. This produces a faster link convergence upon node failure and ultimately ensures a loop free situation. WRP suffers from the same problems that all other table driven protocols suffer from.

5.2.3 Source driven protcols

Source initiated on-demand or reactive routing takes a different approach to table driven routing; routes are only created when a route to a destination is required. The source initiates route discovery process, when the process returns an optimal route is chosen from the set of routes found. This route is established and maintained by a route maintenance process. The route is maintained until it is no-longer required or the destination is inaccessible, via every possible path. Examples of source instated routing protocols are DSR [35], AODV [57], TORA [**?**] and ABR [63].

5.2.4 Dynamic Source Routing

Dynamic Source Routing, DSR was developed by the Monarch project [21] and is a dynamic source routed protocol that carries out on-demand routing. DSR was initially set out in [35] and the current IETF draft is version 5 [37]. DSR is a purely reactive routing protocol that uses source routing to discover routes to the destination. In DSR, a node wanting to sends a packet to another node first sends a *Route Request* packet that is received by all nodes within radio range. If the node knows a route to the destination or is the destination it replies to the originating host with a *Route Reply* packet containing the route to the destination, otherwise it appends itself to the list of hosts traversed by the *Route Request* packet and then retransmits the packet to its neighbours. DSR incorporates a number of techniques to remove route looping etc. In DSR nodes also cache learnt routes in an attempt to reduce the amount of routing related traffic in the network. A follow up paper by Yih-Chun Hu and David B. Johnson [27] discusses the caching strategy used in DSR and explores the use of other strategies. The use of source based routing rather than table based routing imposes an additional overhead on the network, since every packet carries a complete list of the hosts it has traversed. In a power aware environment the additional cost of transmitting the these extra bits of information may be costly. An additionally limitation is as the network grows the size of the control messages and the source routing component of network traffic increases providing DSR with a scaling problem.

In general DSR is well suited to the ad hoc network environment (for which it was designed), the use of on-demand routing means that the level of traffic on the network is a function of the load on the network, the caching strategy used and the size of the network, rather than as a function of time as is in table driven protocols such as DSDV [56]. DSR is not well suited to slowly changing or stationary networks since the overhead placed on the network by source routing is much higher than by table based routing where only deltas to the routing table were sent, as in BGP. However the use of caching and parameters tuned for slow moving networks could reduce this unsuitability in DSR. One of the assumptions made when designing DSR is that it would be used in ad hoc networks where the speed at which hosts host move is “moderate” compared with the packet transmission latency and the wireless range of transmission. This assumption targets DSR to provide routing capabilities for ad hoc nodes that do not change too fast or too slow. In rapidly changing networks the use of caching could adversely effect the performance of a network since the cached route maybe consistently incorrect resulting in packets being incorrectly routed and a *Route Error* packet being sent.

One fundamental floor in DSR is its lack of Multicast support natively in the routing protocol, as is the case AODV.

The experimental section of [35] only examined the performance of DSR in a relatively small environment using a relatively small number of nodes, 24 or less. The scaling properties of DSR to a larger environment and a larger number of nodes were not shown and this is an area of work which should be explored. Another area of experimentation that is lacking is a comparison of DSR against another ad hoc routing protocol such as DSDV, AODV did not exist in 1996.

5.2.5 Ad hoc On Demand Distance Vector

Ad hoc On Demand Distance Vector, AODV was initially set out in [57] and is defined in the IETF Draft, version 8, [1]. AODV is an on demand ad hoc routing protocol that provides both unicast and multicast routing. In contrast to DSR, AODV does not use source routing but rather dynamically creates routing entries in intermediate nodes between the source and destination. ADOV adopts a similar approach DSR in that the source wanting to send information initiates a Route Request, *RREQ*, which is broadcast throughout the ad hoc network until it reaches a node, that maybe the destination itself, which has a route to the destination. This node then propagates back a Route Reply, *RREP* to the source. The traversal of the network by the *RREQ* and *RREP* packets is the mechanism used to establish routing entries in the intermediate tables. Various mechanisms are used to ensure that routing loops do not occur and that only a single path through the ad hoc network is established.

The disadvantages of establishing routing table entries in the intermediate nodes is the entries need to be maintained and expired if they become unused. With source based routing the source of the route is aware of when a route is no-longer required and all that is required is to locally drop the entry, but this is not possible for protocols such as AODV where the intermediate nodes have no knowledge of the usefulness of the route. Techniques such as Route Table Management and Path Maintenance are required to address this issue. To ensure the consistency of a path, nodes must inform other members of the path when they physically move. Movement of the source node initiates a new discovery process, where as movement of the intermediate nodes on the path cause special *RREP* messages to be sent too affected sources. Optionally *hello* messages can be sent, the sending of *hello* messages reduces some of the efficiently of AODV gains by being an on-demand protocol. ADOV includes a mechanism for repairing links that are unexpectedly broken. The upstream node propagates an unsolicited *RREP* with a new sequence number and a hop count of infinity. This *RREP* message is propagated to all active nodes. The source, upon receiving the *RREP* message may restart the discovery process if the route is still required. Forcing the source to re-initiate the discovery process ensures that the route is still required and is loop free, however it is wasteful of resources since it maybe possible for the upstream node which sent the *RREP* message to initiate a local repair of the routing table. This approach is taken in cluster based solutions where each cluster is responsible for the routing through itself.

AODV discovers its immediate neighbours either via observation of the neighbours broadcasts or via *hello* messages that have a limited local scope. The use of local *hello* messages ensures that only nodes with bi-directional links are considered to be neighbours. The inclusion of *hello* messages in AODV is to remove any reliance on the underlying MAC protocol. However these do provide an additional overhead that may be unnecessary; this is acknowledge by the authors and is being investigated to see if it necessary.

The experimental section of the AODV [57] examines the performance of AODV in a much larger range of scenarios than the DSR work [35], showing the performance of the protocol with a larger range of hosts, between 50 and 1000 hosts. However no experimental comparison was made between ADOV and other ad hoc routing protocols, such as DSDV and DSR. The comparison of ad hoc routing protocols is examined in [9] and [13].

5.2.6 Temporally-Ordered Routing Algorithm

Temporally-Ordered Routing Algorithm, TORA was first proposed by Vincent Park and Scott Corson in [52] and its applicability to mobile tactical networks is set out in [53] is defined IETF Draft [5], version 04. TORA is designed to be a highly adaptive source initiated ad hoc routing protocol using link reversal techniques to provide multiple routes for any given source/destination pair. A key concept in TORA is that when a topological change occurs the impact of the resulting control messages should be local in scope, rather than having global scope as in DSR and AODV.

One major disadvantage of TORA is the need for the nodes to have synchronised clocks, a suggested mechanism for clock synchronisation is the use of a GPS time signal. However in some environments, such as on Mars or underwater, it is not possible to have a GPS signal and hence another reliable time synchronisation mechanism is required. Time is a component of the “height” metric used during creation and maintenances phases. The height metric is used to establish a directed acyclic graph routed at the destination and terminated at the source. The “heights” are such that information always flows “down” towards the destination from the source. In [60] it is pointed out that TORA does have the possibility to create oscillations when partitions are being detected concurrently and new routes being built dynamically upon one another, however this is temporary and the routing tables will eventually converge. TORA does not natively support multicast routing.

5.2.7 Associativity-Based Routing

Associativity-Based Routing, ABR [63] takes a different approach to ad hoc routing than other protocols. The approach taken by ABR is to use the most stable route from a source to a destination. Stability is determined by each node periodically broadcasting a beacon, each of its neighbours holds a counter for each of its neighbours and increments the counter for each tick, beacon. The counter is resent each time the node moves out of range. Broadcast discovery is used to discover routes, the returned routes to the source have all the addresses of the nodes in the route and their associativity ticks for their upstream neighbour. The best route is chosen by examining the ticks along the path, the number of hops is used in case of a tie. Using associative ticks ensures that the most stable route is chosen, which is the fundamental objective of ABR.

The use of beaconing and the broadcast discovery imposes an overhead on the network, which could be avoided by only sending beacon messages when then the node is not broadcasting other packets.

5.2.8 Signal Stability Routing

Signal Stability Routing, SSR [15]. Is an on-demand routing protocol that uses the signal strength and the stability of nodes as a routing metric. The protocol is designed to favour routes with a stronger signal. SSR uses periodic beacons to determine signal strength and that it is loop free. However the processing of packets in SSR is slightly convoluted and in general other ad hoc protocols are better designed than SSR, however the concept of using signal strength as a metric is good.

5.3 Power Aware routing protocols

If low power energy devices are to be successful then every aspect of their operation needs to be designed with minimising energy consumption as an objective, ad hoc routing protocols are no exception. In addition to PARO and Leach, power-aware localized routing in wireless networks is describe in [62] and [26].

5.3.1 Power-aware Routing Optimization

Power-aware Routing Optimization, PARO is defined in [18], also see [16] for related work. PARO is described further in [17] and focuses on energy efficiency in personal area networks, such as Bluetooth [19]. PARO takes a similar approach to the work proposed, but limits its scope to a small area where nodes can be in direct radio contact with each other rather than having global routing as proposed here. PARO modifies the transmitter's transmission power to better utilise energy resources. PARO uses a pricing policy based approach where each node determines the price it would charge to forward a packet. For example nodes with non-rechargeable batteries will price their forwarding of a packet higher than a node with a rechargeable battery, or a node with a fixed power supply. The authors acknowledge that PARO lacks "wide area" support and state that this is part of the future work.

5.3.2 Low-Energy Adaptive Clustering Hierarchy

Low-Energy Adaptive Clustering Hierarchy, LEACH is primarily interested in providing a clustering based solution to the problem of low power ad hoc networking rather than adjusting the transmission power of the device. The approach taken by the LEACH work is of interest and could compliment modification of the transmission power of the transmitter. However the LEACH work is a modified MAC protocol upon which is built a routing protocol that uses a clustering algorithm. The cluster head node is randomly rotated amongst the membership of the cluster thus spreading the energy usage of the system across the cluster. The random cluster head allocation algorithm is biased to favour nodes with more remaining energy. Each cluster head schedules the non-cluster head nodes to switch their radios off during all non-transmission periods to increase the lifetime of the device.

5.4 Hybrid routing protocols

Hybrid routing takes the best of proactive and reactive routing and combines the two. The assumption is that inside the zone the network traffic is higher than outside the zone. So if network control traffic is proportional to actual traffic it is less efficient than having control traffic proportional to time. However when traffic is lighter, i.e. outside the zone, then network control traffic proportional to network traffic is more efficient having than control traffic proportional to time. Thus traffic inside the zone is routed proactively and traffic outside the zone is routed reactively. To make hybrid routing efficient the size of the zone must be able to dynamically adjust to changes in traffic patterns.

5.4.1 Zone Routing Protocol

Zone Routing Protocol, ZRP is defined in the IETF draft [23] and has been developed by Z. Hass and M. Pearlman of Cornell University [24].

ZRP is a hybrid routing protocol that groups nodes into zones. Each node proactively maintains a routing table for the nodes within its zone. Outside the zone reactive routing is used. In ZRP the size of the zone can be adjusted dynamically to adjust to the conditions. Hence the degree to which ZRP is proactive or reactive is dependent upon the size of the zone the larger the zone the more proactive ZRP becomes and vice-versa.

Again ZRP lacks the ability to tune the radio device's transmission power, if knowledge of the actual distance between neighbours were known and the radio tuned appropriately, then routing within the zone could be improved further.

5.5 Geographic routing protcols

The use of geographic information can be used to reduce the impact of flooding algorithms, which have been shown to be wasteful of network bandwidth. The idea behind geographic routing protocols is that if you know roughly where a node is it is pointless looking for it, flooding, where you know it isn't, as is the case with other ad hoc routing protocols.

5.5.1 Greedy Perimeter Stateless Routing

Greedy Perimeter Stateless Routing, GPSR is explained in [39] and is a geographically aware routing algorithm. GPSR uses two techniques for forwarding packets, whenever possible it forwards packets in a *greedy* manor, otherwise it use *perimeter* forwarding. Greedy forwarding in GPSR is based upon forwarding to the packet to which ever of your neighbours is closest to the destination, repeating the process until the packet reaches its destination. Node positional information is periodically broadcast to neighbours, this is proactive routing but its effect is minimised by piggy backing the positional information on the back of other data packets. Perimeter forwarding is used to route around radio voids, when a radio void is encountered packets are routed around the edge using a right-hand rule based approach.

5.5.2 Location Aware Routing

Location Aware Routing, LAR, is described in [41]. It is an on demand routing protocol similar to DSR, but uses geographic information obtained via a GPS system to restrict control traffic flooding to an area.

5.5.3 Geography-informed Adaptive Fidelity

Geography-informed Adaptive Fidelity, GAF adds an extra layer of protocol on top of an existing ad hoc routing protocol and the uses the extra layer of protocol to provide information about the energy status of node and is defined in [64]. The system requires nodes to know about there location, via GPS for example, although work is being carried out into only using radio based location techniques. The GAF system splits the network area up into a grid. In a grid square but there maybe any number of nodes only one of them has an active receiver / transmitter, the others are in a sleeping pattern. Each sleeping node periodically wakes up and may swap to being the active node. This technique causes a drop of 40% to 60% in the energy usage of the system [65]. Although GAF imposes an extra overhead on the network it sensibly separates functionality from existing routing protocols. In this way the routing protocol used can be chosen based on the network conditions. GAF and LAR are able to operate seamlessly together.

5.5.4 Fisheye State Routing

Fisheye State Routing, FSR is defined in [3] and is a modified link state algorithm where each node maintains a topology map of the network. Where it differs from other protocols is that it does not flood the network each time a topology change is detected. Periodically each node exchanges the changes it has noticed with its neighbours only. The entries in the tables with the smaller sequence number are exchanged with those with larger sequence numbers, this table exchange process is very similar to the table exchange process of DSDV.

5.6 Cluster based protocols

Clustering groups nodes into geographically close collections, which form peer-to-peer links for communication between nodes in the cluster. Each cluster has a gateway node(s) through which information destined for the outside the cluster must pass. In cluster based networks routing is defined as occurring via clusters rather than via nodes. Each cluster is responsible for routing packets through itself.

The use of clustering and hierarchical approaches to routing are valuable methods of breaking the problem down into manageable components for which tasks or sub-tasks can be allocated. The following pieces of work provide a good starting point for this approach, [44], [13] , [47] , [7] ,[54] and [59]. Although only CGSR is described here.

5.7 Clusterhead Gateway Switch Routing

Clusterhead Gateway Switch Routing, CGSR is a cluster based routing protocol initially proposed in [12]. CGSR is based on DSDV, which has be modified to pass all messages not destined for inside the local cluster to the appropriate cluster gateway node, via the cluster head node. Each cluster has one or more cluster gateway nodes, a cluster gateway node is a node which is in range of one or more cluster head nodes, from one or more different clusters. Each cluster has a single cluster head node is determined using a distributed algorithm, CGSR uses a Least Cluster Change, LCC, algorithm to reduce the amount of time nodes spend electing cluster heads. In LCC the cluster head node only changes when two cluster heads come into contact with each other.

Because CGSR uses DSDV as the underlying routing protocol it is prone to all the inefficiencies associated with it. DSDV is used to periodically broadcast a cluster member table to all nodes in the network, where each node is associated with its appropriate cluster head node. Additionally a routing table is maintained so that nodes know what the next hop to a destination is. When a node receives a packet for a destination it first looks up in the cluster member table the associated cluster head node with the packet and then looks up the in the routing table the next hop to the selected cluster head node.

5.8 A brief comparison of ad hoc routing protocols

As mentioned previously Elizabeth Royer [60] conducted a review of ad hoc routing protocols in 1999, this was a very comprehensive review in which a balanced overview of the key protocols of the day. However since 1999 several key protocols have been developed including ZRP, FSR and GPSR, and a future review should encompass these. A comparison of ad hoc protocols was carried out in [9]. Another comparison was carried out between AODV and DSR in [14]. In particular this survey shows that the two protocols studied show that in an environment with 100 nodes, 40 traffic sources and using a uniform traffic pattern that more control traffic is generated than actual traffic. Caching Strategies for ad hoc protocols are described in [27] but these mainly focus on the effects of different caching strategies when used with DSR.

5.9 Multicast routing in ad hoc networks

Little work has been done in the area of Multicast routing in ad hoc networks, in general the assumption has been made that like fixed networks multicast routing will be built on top of unicast routing. However Obraczka et al. [51] propose that this is not efficient for ad hoc networks due to their broadcast nature and that multicast routing should be implemented independently.

5.9.1 AODV

As previously stated AODV is one of the few ad hoc routing protocols that natively supports multicast communications.

5.10 Low Power Radio

The radio technologies of particular interest to this piece of work are the 802.11 and 802.15 series of IEEE standards. These standards have been focused upon because real world implementations from different manufacturers exist and hence can be used to carry out practical validation of simulations.

5.10.1 IEEE 802

The IEEE 802 [3] set of standards define the Local Area and Metropolitan Area network protocols. The 802 standards are limited to defining layers 1 (Physical) and 2 (Data Link) of the ISO Open Systems

[3] The IEEE 802 committee first met in February 1980, hence 802

Interconnection Model. This framework is set out in [31]. The 802 series of standards also includes a set of standards for wireless communications in particular wireless lans (802.11) and wireless personal area networks (802.15). It is these which of interest to us.

802.11 Wireless LAN MAC and Physical Layer specification
The two standard 802.11a and 802.11b are both supplements to the 802.11 standard. 802.11 is specified to operate in the 2.4 GHz, unlicensed ISM band and defines both 1Mbps and 2Mbps bandwidths using different modulation technologies. These are:-

- 2Mbps (1 Mbps noisy) Direct Sequence Spread Spectrum (DSSS)
- 1Mbps (2 Mbps noiseless) Frequency Hopping Spread Spectrum (FHSS)

It also operates in the infrared spectrum providing 1Mbps and 2Mbps bandwidths. Both 802.11a and 802.11b both use Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for the MAC layer with the only modification being to the physical layer. Hence the different data rate communications can co-exist allowing a transition to higher data rates.

802.11a (5 GHz)
The 802.11a standard supplements 802.11 and operates in the 5 GHz band and uses Orthogonal Frequency Division Multiplexing (OFDM) and optionally supporting data rates of 9, 18, 36, 48 and 54 Mbps and mandatory supporting data rates of 6, 12, and 24 Mbps. However the increase in data rates are not without a cost, the range of transmission is reduced. Noise, protocol overheads and interference/error correction reduces the actual data rates available to applications.

Proxim Inc. has recently released a 100Mbps version of 802.11a [33] by using Proxim's 2X technology (released 10/08/2001). The use of 802.11a hasn't yet been approved for use in Europe, it is expected to be approved in the middle of 2002.

802.11b (2.4 GHz)
The 802.11b standard supplements 802.11 and operates in the 2.4 GHz ISM band and uses Direct Sequence Spread Spectrum (DSSS) and can operate at 1, 2, 5.5 and 11 Mbps. This standard is commonly known as Wavelan and is widely deployed in Office type environments.

802.15 Wireless Personal Area Networks
Wireless Personal Area networks are designed to provide short range, low data rate communications, effictively removing the need for wires between every day devices such as mobile phone and hands-free kits.

802.15.1 Bluetooth
The Bluetooth consortium has developed Bluetooth [19] and is in the process of IEEE standardisation as IEEE 802.15.1 [29]. Bluetooth has been developed to provide device interconnection, using low cost components $10 or less and provide seamless connectivity. Bluetooth operates at either 1Mb/s or 2Mb/s using FHSS, frequency hopping spread spectrum encoding. Bluetooth is becoming increasingly popular with products already available.

802.15.4 Zigbee
Zigbee is being developed by the Zigbee working group [6] and is being standardized as IEEE standard 802.15.4.Zigbee is a master-slave style network designed for use in home automation type tasks. It has been explicitly designed with the goals of keeping the cost of manufacture low, $1 per radio system or less and being very low powered (6 months to 2 years on 2 AA batteries). The master-slave model is designed

to reduce the energy costs of slave devices to the extent that wireless light switches are feasible. Zigbee also includes the following features[4]:

- master/slave topology
- automatic network configuration
- dynamic slave device addressing
- power management features
- CSMA-CA channel
- service discovery
- 250 kbps and 28 kbps rates

A negative point of Zigbee is that it has no mechanism to change the transmission power of the radio, it is fixed. Zigbee also inverts the traditional model of radio transmission being more expensive than reception rough figures for receive power is 60mW and transmit is 1mW due to the signal processing involved.

5.11 Simulators

Several simulators are available for modelling ad hoc networks are available. The key simulators are OPNET [32], GLOMOSIM [20] (based on Parsec) and NS version 2 (Network Simulator) [22].

5.11.1 NS

NS is an event driven network simulator written using a combination of C++ and TCL (more specifically OTCL). NS was initially written by the Network Group at LBL and is now maintained by ISI/UCB and is distributed under a range of different licenses, but is an open source style project. One of the main advantages of NS is the range of contributed code, yet this is also one of its main disadvantage with contributed code sometimes breaking existing code. The Monarch [21] project at CMU added mobility support to NS and it now supports 5 different ad hoc routing protocols in the main source distribution with numerous others being available from other locations.

5.11.2 GlomoSim

Glomosim is an event driven simulator for mobile systems, it is built on top of the Parsec parallel simulation environment. Glomosim is written in C, and provides a set of well defined interfaces to components of the system. Unlike NS, Glomosim is completely compiled it has no scripting language components, which should provide for faster simulations. Glomosim supports a slightly smaller number of simulation protocols compared with NS.

5.11.3 OpNet

OpNet is a commercial network simulator for which a number of ad hoc protocols have been developed including AODV and ZRP. Since this is a commercial simulator this has not been investigated further.

[4] Source Zigbee Group Website [6]

6 Appendix B - Timeline

The work is to be split into four, six-month sections. The first three components are the testing the hypothesis sections detailed in the main body of the document and the final six months is designated for writing-up. In general the experimental components will be split up as:

- 4 weeks : Experimental planning.
- 8 to 10 weeks : Experimental development, coding and other related tasks.
- 3 to 4 weeks : Experiment 1.
- 3 to 4 weeks : Experiment 2.
- 3 to 4 weeks : Experiment 3.
- 1 to 2 weeks : Analysis and writing up.

Where possible Experiments 1 to 3 will be decoupled from each other, to allow for parallel work.

7 Appendix C - Work so far

The work so far has focused upon experimentation with the NS simulator, and a literature review.

7.1 NS work

Node Suicide patch
This patch modifies NS to provide the ability to terminate a node's activity by setting the node's energy level to zero. This is to simulate the random failure of a device due to malfunction or geographic reasons i.e. falling down a hole or running off a cliff.

ZRP upgrade
I felt that ZRP was an important ad hoc protocol and was lacking in the later versions of NS, and significant changes in the architecture of NS meant that it was not trivial to apply the existing patch that worked for previous versions of NS. The original ZRP patch was written by Robin Poss [58].

Simulation work
The focus of this work has been two-fold, firstly to gain experience in carrying out ad hoc network simulations and secondly to examine the effect of different ad hoc routing protocols on the energy consumption of a collection of nodes.

The experiment examined the effect of 4 different ad hoc routing protocols, (DSR, AODV, TORA, and DSDV) on a collection of 50 in a planar environment (400 x 400). Each experiment lasted for 600 seconds, every second each node randomly choose to move, communicate or die (fail), the threshold for the occurrence of each event was pre-determined. The experiments were broken down into groups, each group of experiments consisted of a set of threshold parameters and a set of random number generator seeds. The same seeds and threshold values were used to initiate one experiment per protocol. Using the same seed values ensured that the mobility, communication and failure patterns experienced by the nodes in the network were the same, except for variations due to the protocol. Each experiment was repeated 8 times using the same threshold values but different seed value to reduce the influence of the random number generators on the results.

The lessons learnt from carrying out ad hoc network simulations are firstly the amount of data generated is huge. The experiment detailed above generated in 6 cdroms of compressed simulation trace data. This volume of data necessitated the development of scripts to process the raw data from directly from the cdroms. The reason for storing the trace data from the simulation to cdrom is two-fold, firstly it ensures that the data is archived and secondly the analysis of such a large amount of data is non trivial especially where simulations have failed.

Partial analysis of the data has been carried out but not completed.

7.2 Literature review

This is Appendix A of this report.

8 Appendix D - Thesis Table of Contents

- Abstract
- Keywords
- Table of Contents
- Copyright Statement
- Chapter 1 - Introduction
- Chapter 2 - Background and related work
  - Literature Review
- Chapter 3 - Hypothesis
  - Hypothesis Statement
  - Discussion of Hypothesis
- Chapter 4 - Testing Hypothesis 1
  - Aims and Objectives
  - Methodology
  - Experiment 1
  - Experiment 2
  - Experiment 3
  - Analysis
  - Results and Conclusions
- Chapter 5 - Testing Hypothesis 2
  - Aims and Objectives
  - Methodology
  - Experiment 1
  - Experiment 2
  - Experiment 3
  - Analysis
  - Results and Conclusions
- Chapter 6 - Testing Hypothesis 3
  - Aims and Objectives
  - Methodology
  - Experiment 1
  - Experiment 2
  - Experiment 3
  - Analysis
  - Results and Conclusions

- Chapter 7 - Conclusion
- Chapter 8 - Future work
- Appendix A - References
- Appendix B - Extra Graphs and Figures
- Appendix C - Other information

9 Appendix E - Possible scenario

A problem domain that is of particular interest is the use of low power radio devices in disaster and earthquake zones or mine and building collapses where the rescue scene maybe dangerous for the rescuers or where there are an insufficient number of people to search the area quickly and effectively enough to rescue survivors. As has been shown in the recent World Trade Center disaster robotic devices are able to explore areas of a collapsed building that a person is unable to reach. By taking the idea of using robots in collapsed areas to carry out sensing tasks one stage further it would be interesting to make the building itself a sensor by embedding sensors into the fabric of the building, there are already numerous sensors in many building ranging from movement sensors for automatic lighting systems and anti-theft systems to temperature sensors for heating regulation and fire detection, this is not taking into account the numerous other systems that could host low power radio systems such as lights, id badges and even coffee cups. However imagine if the low power sensors were attached to walls either by embedding them in the wall or by bolting them to it and had the ability to sense their immediate surroundings. The sensors need not have to have the ability to process the data they sense but must be able to store it for a period of time and/or relay it via a radio device. Thus it would be possible to pass by the low power sensors with another devices and extract the information that they hold. From this information it could be possible to build a three dimensional map of the building. Now if the building collapsed, and a robot device were sent to explore the rubble a three dimensional map of the rubble could be created and the areas big enough to allow people to survive in identified. The problem of exploring a collapsed building cannot be partitioned into grid like zones where one robot has to search a physical area to complete its task because the rubble will create tunnels and dead-ends which obviously do not fit a grid like structure. Instead a better solution perhaps might be that the robots are distributed across the scene and collectively told to explore the zone. To collectively explore the zone the robots must communicate with each other to propagate the information that they have discovered from the sensors they have themselves or those embedded in the building. Thus the three dimensional map of the searched area is propagated to those searching.

However a situation as complex as exploring a collapsed building is too complex a problem to initially investigate so a similar problems of investigating a planar environment where the energy usage of the system is an important aspect, and in particular the energy usage of the communications system as a whole. Where the system is taken to be all the nodes involved in the particular task assigned to them as a collective.

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