An Adaptive Routing Mechanism For *Ad Hoc* Wireless Sensor Networks

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Abstract An adaptive routing mechanism is described that generates routing paths dynamically for a network of *ad hoc* wireless sensor nodes. The mechanism enables sensor nodes to minimize route cost by varying their transmission range, and by experimenting with the neighbours from which they forward data. Three route cost functions were compared. The route cost function that sums the link costs was found to give the worst performance, both in the proportion of packets delivered and the standard deviation of packet origins.

1. Introduction

Scientific monitoring has typically had to rely on data collected from a handful of localized, 'heavy-duty' sensor installations. A wireless *ad hoc* sensor network is a collection of battery-powered devices which have very small processors, and typically communicate by radio. They are designed to be cheap enough that they can be deployed in large numbers, in order to take comprehensive measurements from the environment. The sensor nodes need to be able to self-configure, in order to route the measurements back to network sinks. They may also need to determine their locations, and to determine desirable operating behaviours, co-operatively, in order that the data generated by the network answers the needs of the network users as closely as possible, with minimal management.

Such wireless *ad hoc* sensor networks are not necessarily an end in themselves, in research terms. Design efforts in this field pave the way for networking with more 'mainstream' markets, such as the field referred to as *ubiquitous computing*. Here, tiny autonomous, wireless devices are envisaged as being integrated into people's daily lives in order to increase the flexibility of lifestyle options, e.g. care at home for the infirm, or to give timely access to spatially distributed information, e.g. co-ordinating supply chains.

2. Related Work

Many *ad hoc* routing protocols have been devised. Some of the most widely known are DSDV[1], TORA[2], DSR[3] and AODV[4]. A comparison of the performance of these protocols[5] has shown widely differing results in the size of routing overhead. However, the main problems with using these protocols in a network of mobile sensor devices is that

1) the size of processor and memory required are too large, and
2) the protocols are not energy usage aware.

Sensor networks are envisaged as consisting of very small, very cheap microprocessors, e.g.16 bit, with 32 kbytes of RAM. They will also have a finite battery supply, which will be difficult, and probably not desirable to replace. It is therefore very important that any communication protocol is energy-efficiency aware, and also pared to a minimum in communication overhead and memory usage.

Work by Cerpa *et al*.[6] refers to habitat monitoring as a driver for wireless communications technology, and focuses on power-saving by nodes outside regions where interesting changes could be observed, switching themselves off, and being triggered to switch back on only when interesting activity is detected in their vicinity. Work by Xu *et al*.[7] again focuses on using powered- down modes for devices, based on whether data traffic is predicted or not, and on the number of equivalent nodes nearby that could be used for alternate routing paths. However, the assumption here is that the underlying routing will be based on conventional *ad hoc* routing protocols such as AODV[4]. Whereas, sensor networks typically would require a lighter weight approach to routing, where decisions are based on information from immediate neighbours only.

A lot of work has been done at the University of California and the Intel Berkeley Research Lab, to develop operating systems and networks for small *ad hoc* sensor devices, known as the *Smartdust*[8] project, for which *TinyOS*[9] has been developed. However, the routing scheme they refer to is not currently power-aware, but rather uses a hierarchical structure to find shortest paths to the sinks.

3. Adaptive Routing Mechanism

The aim of this work was to find a dynamic way to maintain an efficient routing structure with minimal overhead. The method is an extension of the routing hierarchy used by the *Smartdust*[8] project, in which the network sink or sinks initiate a cascade of local broadcasts that allow shortest paths to be established, by identifying each layer in the hierarchy with a level number. Data forwarding is only allowed from nodes of a greater level number, where the sink is at level 1. The extension to this, is to have dynamic updates of node levels according to locally exchanged information as part of data transfer, so that changes in network configuration propagate quickly, reinstating a data-flow structure, with minimal protocol overhead. The forwarding decision should also be very simple. Forwarding is triggered when a node's buffer exceeded a threshold of a fraction of its maximum capacity.

Route cost is communicated to nodes dynamically, as part of data transfer, in order to influence routing decisions so as to minimize route cost. Nodes acknowledge the receipt of data packets by passing down a reward to a transmitting device, as well as the receiving node's hierarchical level. Rewards are passed back, away from the sink, upstream in data flow terms, to forwarding devices. This reward is proportional to the quantity of fresh data received, but also has a form that will favour certain forwarding behaviour. Three route cost metrics have been investigated:

maxexp is the maximum value of $e^{r_i^2 / susp_i}$ *Eqn* 1

for devices, i, that form a routing path towards the sink, where r is the broadcast radius of the device and $susp$ is the square of the sustainable broadcast radius, which is given by (battery level left after sending own sensor measurments)/(quantity of data expected to forward) until the end of the experiment. The estimate of the data that will be forwarded is based on a rolling average of rate of data forwarding.

Two other cost functions were considered. Both have been referred to in a paper by Toh *et al*.[10]. One considers the cost of a route as the sum of the costs of the links that form the route, and will be referred to as cost function *sum r squared*, and has the form, for a route from A to D, containing devices A,B,C and D, of

$$sumrsquared_{ABCD} = r_{AB}^2 + r_{BC}^2 + r_{CD}^2 \quad . \qquad Eqn\ 2$$

The other,

maxbatt, is the maximum value of B_i^0 / B_i, *Eqn* 3

for devices in a routing path to a sink, where B_i^0 is the starting battery level and B_i is the current battery level of device i.

The way in which this approach is adaptive, is that a node periodically varies its range or forwarding behaviour, and then either adopts or rejects this new behaviour according to having gained higher or lower reward during the experiment than previously. Nodes are not obliged to forward data from all nodes of higher level number. The nodes test a proposed new operating behaviour against a 'sustainability' criterion, by calculating

$$gauge = e^{-r_i^2 / susp_i} \quad . \qquad Eqn\ 4$$

This is compared against a uniform random number, rn, between 0 and 1, which is a similar approach to the use of the Metropolis criterion[11]. If the proposed new range is less than previously, then this is accepted automatically for experimentation; but to increase a node's range, $rn > gauge$ must be satisfied. Similarly, if $rn > gauge$, then a node may alternatively experiment with adding another neighbour node to its list of nodes from which it will forward data whereas, if $nr \leq gauge$, then a device will experiment with removing a node from its list of nodes from which it will forward data. These tests simply keep the choice of experimental operating behaviours within reasonable bounds.

4. Simulation

Simulations were carried out for a small network of 9 sensor nodes around a network sink, with, on average about 2000 data packets generated by each sensor, to yield about 24000 packets as the maximum number of packets that could in principle be stored at the sink by the end of the data-gathering experiment.

Devices had a buffer capacity of 30 packets of data. They had cache memories for remembering the identifiers of the last 60 packets they had seen. Devices were triggered to broadcast data, at the end of a receive transmission, or after adding their own sensor data to their buffers, when the quantity of data in the buffer exceeded 3/10 of the maximum buffer capacity.

Inter-node distances were assumed sufficiently large (>60 m) that the cost of data transmission was the dominant energy cost. The transmission energy dissipation was taken as r^2, where r is the inter-node distance. There was also a small constant cost of sending any transmission, and a small constant cost of taking a sensor measurement. Receive energy cost was neglected. Data aggregation was not modelled, but is likely to offer significant advantage, especially if it were achieved as a form of node specialisation using mobile code, as in *active networks*[12].

5. Results

The following sets of results are each the averages of ten simulations. The first set of experiments compares results, using the cost function *maxexp*, described above, with and without tests to constrain experiments within reasonable bounds.

Delivered packets as % of max. possible, using *maxexp* cost function, with and without sustainability tests

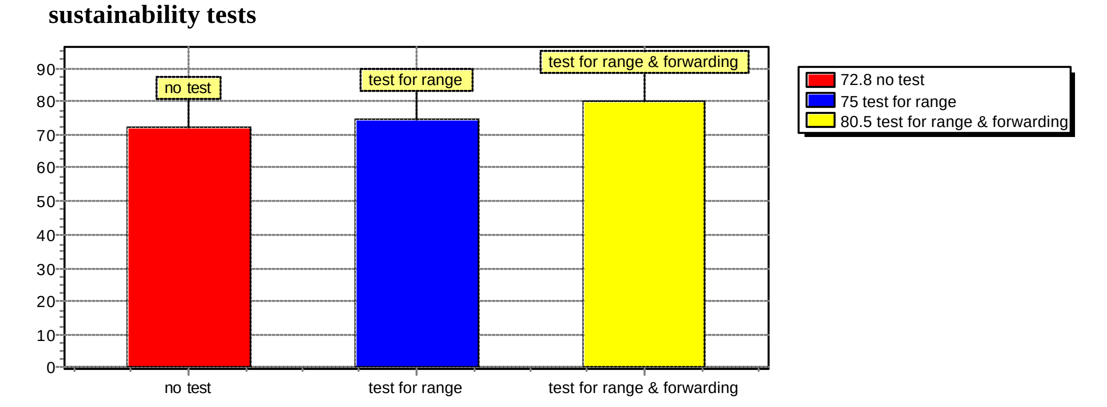

***Figure* 1**

Delivered packets as % of max. possible, for different cost functions

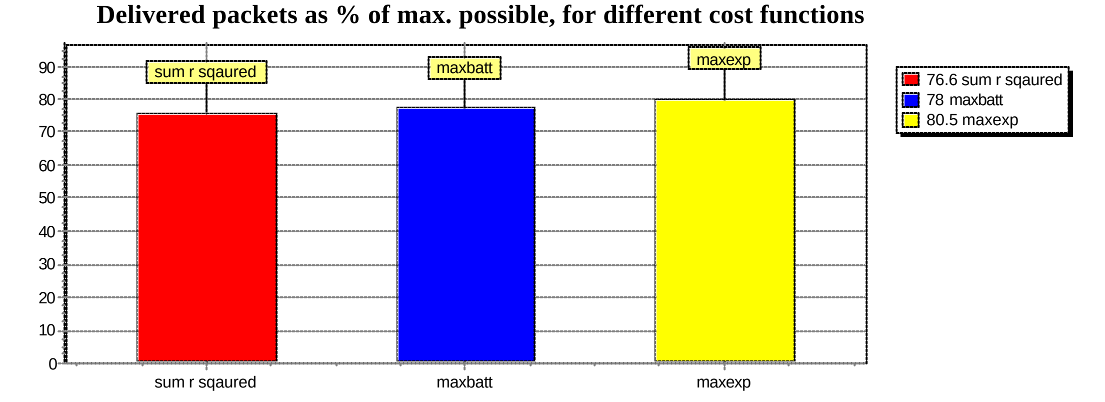

***Figure* 2**

The results given in *Figure* 1 refer to the percentage, as a fraction of all data measurements taken by devices in the data-gathering experiment, of data packets collected at the sink. A greater proportion of data is collected at the sink when devices are constrained to experiment with their operating behaviours within limits.

Having concluded that these 'sustainability' tests were useful for choosing operating behaviours, they were used for the remaining experiments, comparing the performance of the three cost functions given by *Equations* 1, 2 and 3: *maxexp, sum r squared, and maxbatt.* The results in *Figure* 2 give the percentage, as a fraction of all data measurements taken by devices in the data-gathering experiment, of data packets collected at the sink. The cost function *maxexp* results in a slightly higher proportion of data being collected at the sink than *maxbatt*, which is slightly higher than *sum r squared*.

6. Discussion

These results are of limited scope and represent a system that has been modelled fairly simplistically. However, the handing down of costs/rewards with data transmission acknowledgements has enabled a routing strategy to be implemented that is more sophisticated than 'shortest path first', whilst requiring minimal communication overhead, and very limited memory. Although node mobility has not been modelled explicitly, changes in node range and forwarding behaviour represent pseudo-mobility, and moderate mobility would be a straight-forward extension of this.

The network topology was chosen so that, if the nodes had a small fixed range, data would have followed a linear path through all 9 sensor nodes, before reaching the sink. This case is favoured by the cost function that minimizes the sum of link costs. However, this linear routing puts undue load on the nodes nearest the sink. To maximise the quantity of data collected, there is a trade-off between the energy cost of a route and the cost of the route in terms of loss of integrity of the network.

Using the sum of link costs as the route cost, delivers fewer packets than when using the costliest node as the route cost. Further results showed that the ratio of standard deviations of delivered packet origins for 'maxbatt', 'maxexp' and 'sum r squared' was 1 : 1.12 : 1.18. The 'sum r squared' cost function gave the highest standard deviation of delivered packet origins, which is a disadvantage, as it means less even sampling coverage. These results are consistent with the conclusion that using the sum of link costs as the route cost has a damaging effect on network integrity, compared with cost functions that use the costliest node in the route as the route cost.

References

[1]C Perkins and P Bhagwat, Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for mobile computers, *Proceedings of the SIGCOMM '94 Conference on Communications Architectures, Protocols and Applications*, pages 234-244, August 1994

[2]VD Park and MS Corson, A Highly Adaptive Distributed routing Algorithm for Mobile Wireless Networks, *Proceedings of INFOCOM '97*, pages 1405-1413, April 1997

[3]DB Johnson, Routing in Ad Hoc Networks of Mobile Hosts, *Proceedings of the IEEE Workshop on Mobile Computing Systems and Applications*, pages 158-163, December 1994

[4]C Perkins, Ad Hoc On Demand Distance Vector (AODV) Routing, *Internet-Draft, draft-ietf-manet-aodv-04.txt,* October 1999

[5] J Broch, DA Maltz, DB Johnson, Y-C Hu, J Jetcheva, A Performance Comparison of Multi-Hop Wireless Ad Hoc Routing Protocols, *Proceedings of Mobicom '98*

[6]A Cerpa, J Elson, D Elstrin, L Girod, M Hamilton and J Zhao, Habitat Monitoring: Application Driver for Wireless Communications Technology, *ACM SIGCOMM Workshop on Data Communications in Latin America and the Caribbean*, Costa Rica, April 2001.

[7] Y Xu, J Heidemann, and D Estrin, Adaptive energy-conserving routing for multihop ad hoc networks, *Tech. Rep. 527, USC/Information Sciences Institute*, Oct. 2000.

[8] L Doherty, Algorithms for Position and Data Recovery in Wireless Sensor Networks, *UC Berkeley EECS Masters Report*, May 2000

[9]DE Culler, J Hill, P Buonadonna, R Szewczyk, and A Woo, A Network-Centric Approach to Embedded Software for Tiny Devices, *EMSOFT 2001: First International Workshop on Embedded Software*, Oct. 2001

[10] CK Toh, Maximum Battery Life routing to Support Ubiquitous Mobile Computing in Wireless Ad Hoc Networks, *IEEE Communications Magazine*, June 2001, **2**

[11] N Metropolis, AW Rosenbluth, MN Rosenbluth, AH Teller and E Teller, *J. Chem. Phys.,* **21**, 1087, 1953

[12] DL Tennenhouse, JM Smith, WD Sincoskie, DJ Wetherall, GJ Minden. A Survey of Active Network Research. *IEEE Communications Magazine* 1997 vol 35. No 1. P80-86.