Localised Topology Measurement and Control in Wireless Sensor Network

Lamling Shum and Lionel Sacks

University College London

Abstract: This paper reviews the problem of topology control with the model of Unit-Disk Graph. We looked at the existing protocols and divided them into physical layer, which deals with range assignment problem and logical layer, which deals with link pruning. We observed that new metrics can be developed to enhance physical topology control, and noted that dynamic solutions including probabilistic broadcasting to minimise transport energy costs may have advantages over logical topology control.

1. Introduction

Wireless sensor networks (WSN) have received increasing attention in the research fields and are distinguished from the mobile ad-hoc networks (MANET) because of their special characteristics arisen from the functional requirements. WSN are generally composed of large number of nodes distributed in a wide coverage area for monitoring and environmental measurement. Similar to MANET, the basic requirements of WSN are distributed, scalability, robustness, self-organising and energy conservation. In-network processing is encouraged to minimise the need for long-distance communication in saving battery power. In addition, the computational power on sensor nodes is limited due to their low-cost requirement and hence, algorithms are required to be simple [1].

Sensor networks are used in many applications such as target tracking [2], ocean floor monitoring [3] and body sensor networks [4]. The deployment of sensor network varies from manual placement of individual sensors, scattering in a large field by transport, to sensors automatically move to pre-programmed or calculated locations. Sensor nodes can be stationary, drifting or mobile, making networking a real challenge and application specific. The networks are always dynamic due to node movement, environmental changes, addition and removal of nodes. These characteristics in WSN have imposed very different requirements for developing network, and application protocols and knowledge of network connectivity is useful for optimisation.

Topology control and its derivatives have been proposed in WSN and MANET for achieving the connectivity and energy conservation requirements. Its objectives include network monitoring to ensure critical information gathered from the network can be sent back to the users timely and accurately; increase network capacity by reducing the amount of interference generated from redundant transmitting nodes; energy conservation by reducing radio transmission power and collision; and network connectivity strengthening.

The above problem can be tackled in 2 levels, physical and logical. At the physical level, topology control can be achieved by assigning the optimal transmission range. The major objective here is to establish a strongly connected network fulfilling the requirements of redundancy and delayed while minimising energy cost. At the logical level, we tackle the communication graph problem to achieve minimum cost in terms of energy, distance, *etc* for network unicast and broadcast. This involves removing redundant neighbours from the communication list. Another less studied possibility of topology control is relocation of nodes to an optimal position. This, however, very much depends on the application whether reposition of nodes, either manually or automatically is feasible.

This paper attempts to briefly review the research in topology control and identify areas for future research.

2. Representation of WSN

While most WSN are meshed network, linear, ring or star are also possible topologies. A commonly used model in research for WSN is the *Point-graph model*, or *Random Geometric Graph (RGG)* or *Unit-Disk Graph (UDG).* Under this model, the nodes' positions are chosen according to some probability distribution and nodes are connected if they are within the 'disk' of communication range.

In [5], graph notations are used to define the model. A *d*-dimensional network, with *d*=1,2,3 is represented by $M_d=(N, P)$, where *N* is the set of nodes, with $|N|=n$, and $P: N \times T \rightarrow [0,l]^d$, for some $l>0$, is the placement function. The placement is dependent on the time *t* and in most research, *P* is considered *stationary* which means the placement does not vary with time. Hence, *P* can be simplify as $P: N \rightarrow [0,l]^d$.

Range assignment for M_d is a function $RA: N \rightarrow (0, r_{\max}]$ that assigns to every element of *N* a value in $(0, r_{\max}]$ representing the transmitting range and $r_{\max}$ is governed by the physical characteristics of the radio transceivers.

The *communication graph* induced by *RA* at time *t* is a directed graph $G_t = (N, E(t))$ where edge (i, j) exists if and only if $RA(i) \geq \delta_{p(i,j),p(j,t)}$. $\delta_{P(i,j),P(j,t)}$ is the Euclidean distance between *i* and *j* at time *t* with power *p*.

The power p_i required by node *i* to correctly transmit data to node *j* must satisfy inequality $\frac{p_i}{\delta_{i,j}^{\alpha}} \geq \beta$ where $\alpha \geq 2$ is the distance-power gradient, $\beta \geq 1$ is the transmission quality parameter and $\delta_{i,j}$ is the Euclidean distance between the nodes [6]. α is often used to define transmission cost, *e.g.*, the energy cost of RA is defined as $c(RA) = \sum_{i \in N} (RA(i))^{\alpha}$.

Research in UDG involves a variety of topics including *minimum cut set*, *minimum spanning tree, separated pair, etc*. They have high relevancy to our research on connectivity and energy cost minimisation in WSN. However, it is noted that although most consider UDG is a simple and adequate model for WSN, it is important to understand the differences to reality. UDG does not take geographic and environmental variations within the network into account. The temporal variation including mobility is not reflected in the model. These variances are important towards successful implementation. Other models derived from UDG exist to improve the accuracy of the model [7].

3. Physical Topology Control

In this layer we consider the range assignment problem and obtain a maximum communication graph $G_{mt} = (N, E_m(t))$. $E_m(t)$ contains all the edges that satisfy the $RA(i) \geq \delta_{p(i,j),p(j,t)}$ criterion. Physical topology control depicts the connectivity in the MAC communication layer. Common MAC protocols including CSMA and TDMA usually require that G_{mt} to be *undirected*, hence, links are bi-directional.

If all the nodes have the same range, we are looking at the *r-homogenous* range assignment problem, which is also known as the critical transmitting range. If the positions of all the nodes are also known, the problem is reduced to finding the longest edge in the *minimum spanning tree (MST)* of G_{mt} . However, in most real application this is not possible. The goal is then to characterise the minimum value of *r* which achieve a connected graph with high probability (w.h.p.), *i.e.*, with probability that tends to 1 as the number of nodes increases. The results presented in [8] have shown that the critical transmitting range for connectivity w.h.p. is $r = c\sqrt{\frac{\log n}{n}}$ for come constant $c > 0$. This has provided a starting point to the heterogeneous range assignment problem where nodes have different ranges to each other.

The solution for heterogeneous range assignment needs to be distributed. The concept of complex systems may be applied where local non-linear coupling rules leads to global phenomena. Locally nodes reinforce or reduce their connectivity using information obtained in the neighbourhood.

The *k-Neighbours* approach in [9] uses just the number of information and estimate the value *k* that guarantees connectivity of the communication graph w.h.p. and the degree is logarithmically bounded at each node. Cone Based Topology Control (CBTC) achieves similar goal using directional information [10]. Both approaches, and other protocols try to find the minimal range assignment which would produce a *connected* communication graph and *a bounded maximum node degree* to limit the amount of interference. Metrics such as number of neighbours and the cone angles are used to indicate the local connectivity for the optimisation. We address two issues here. Is being a connected network an adequate criterion for a healthy network? A linear topology produce a connected network, however, having a *vertices-cut-set* of 1, a single node failure would disconnect the network. This leads to the second question, what metrics can we use to measure the connectivity locally and construct a stronger network structure?

We attempt to look for, and develop a set of metrics that can represent local redundancy more accurately and in turn reflect network connectivity. Our range assignment objective is to produce enough redundancy to guarantee network integrity, and to minimise total energy usage and interference. Thus, we can make use of measures such as *k-connectivity* and bounded maximum node-degree to evaluate the range assignment solution.

4. Logical Topology Control

In this layer we construct a subgraph *G'* of G_m which contains a subset of edges $E'(t) \in E_m(t)$. The goal of the pruning process is to reduce redundancy and consecutively the total energy cost for delivering messages[1]. The problem is related to the type of network traffic and transport mechanism in the network layer. Unlike physical topology control, there is no strict requirements for *G'* to be undirected.

In unicast, logical topology control focuses on computing topologies which have energy-efficient *paths* between source-destination pairs and the problem is to find the minimum power cost $pc(P) = \sum_{i=1}^{k-1} \delta_{u_i,u_{i+1}}^{\alpha}$ over all the paths for all the node pairs *u* and *v* in Graph *G'*. *Distance stretch factor*, and *power stretch factor*[5] are commonly used to evaluate the efficiency of the algorithm. The construction of proximity graphs including Relative Neighbourhood Graph (*RNG*) and Gabriel Graph (*GG*) based on the position of the neighbour nodes are examples of simple and distributed solutions to the problem.

Broadcast stretch factor based on the power cost of the broadcast tree $pc(T) = \sum_{v \in N} pc_T(v)$ is used to evaluate protocols for optimising network broadcast. One of such algorithms is LMST[11], which attempts to minimise the cost of spanning trees by using greedy method. Another example is XTC [12], which order its neighbours according to the received link quality information. The lists are exchanged amoung the neighbours and are used as the basis for optimisation.

We note that logical topology control has similar objectives to other research areas including clustering, probabilistic broadcasting and the search for connecting dominant set (CDS) that they attempt to find an energy efficient, localise and dynamic way of relaying information in WSN. Logical topology control and CDS are deterministic solutions, which produce the same topology given the same network configuration. There may be issues of unbalanced role and energy usage among the nodes and the protocols may be less adaptive to sudden changes. Hence, dynamic solutions including probabilistic broadcasting and dynamic clustering may have advantages over topology control in tackling transport problem in WSN.

5. Conclusion and Future Work

In this paper, we have briefly reviewed the existing topology control mechanisms. We introduced some notations used for representing Unit Disk Graph, which is a model commonly used for evaluating wireless sensor network. We divided topology control into two layers: Physical and logical, and identified the research objectives, considerations and evaluation criteria for each layer.

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[1] Please note that this is defined differently from the normal *minimum energy unicast and broadcast* problem [8], that the maximal graph *G* is defined such that all nodes are transmitting with maximum range.

While most research concentrate on identifying the optimal topology control graph or algorithm, they underestimate the limitations on what can be controlled and measured. The limitations are particularly prominent in the WSN case as simple equipment is used. Information like precise location and direction may not be available. It may not be feasible to manually manipulate node positions. The transmission range and intervals available for tuning may be so limited that it would not make a significant contribution to the overall topology.

Hence, we would like to emphasise the importance of topology measurement. First of all it provides a starting point to when control is necessary. Secondly, when nothing can be done to automatically remedy the weakness, at least nodes can report to the users and they may do something about it. We observe that there is space in the physical topology control for further research provided that alternative metrics is identified, which may improve the results in terms of network connectivity and energy cost minimisation.

Finally, more research is required to compare the advantages of logical topology control and other transporting optimisation algorithms. We observe that a dynamic solution such as probabilistic broadcasting and dynamic clustering may be preferred since energy usage may be more even across the network and it may be more adaptive to sudden changes.

6. References.

[1] I.F.Akyildiz, W. Su, et al, *A Survey on Sensor Network*, IEEE Communications Magazine, August 2002.

[2] Hanbiao Wang, Jermy Elson, Lewis Girod, Deborah Estrin, *Target Classification and Localization in Habitat Monitoring*, Proceedings of the IEEE ICASSP, Hong Kong, April 2003.

[3] L Sacks, M Britton, I Wokoma, A Marbini, T Adebutu, I Marshall, C Roadknight, J Tateson, D Robinson and A G Velazquez, *The Development of a Robust, Autonomous Sensor Network Platform for Environmental Monitoring*, IoP Sensors and their Applications, 2003.

[4] Roozbeh Jafari, Andre Encarnacao, Azad Zahoory, Foad Dabiri, Hyduke Noshadi and Majid Sarrafzadeh, *Wireless Sensor Networks For Health Monitoring", The 2nd ACM/IEEE International Conference on Mobile and Ubiquitous Systems (MobiQuitous)*, July 2005.

[5] Paolo Santi, *Topology Control in Wireless Ad Hoc and Sensor Networks*, ACM Computing Surveys, vol. 37 , issue 2, p.164-194, June 2005.

[6] K. Pahlavan and A. Levesque, *Wireless Information Networks*, John Wiley and Sons, New York, 1995.

[7] Fabian Kuhn, Roger Watterhofer and Aaron Zollinger, *Ad-hoc Networks Beyond Unit Disk Graphs*, Proceedings of the 2003 joint workshop on Foundations of mobile computing, Pages: 69 – 78, San Diego, CA, USA, 2003.

[8] P. Panchapakesan and D. Manjunath, *On the transmission range in dense ad hoc radio networks*, In Proceeding of IEEE SPCOM, 2001.

[9] Douglas M. Blough, Mauro Leoncini, Giovanni Resta and Paolo Santi, *The k-Neighbors Approach to Interference Bounded and Symmetric Topology Control in Ad Hoc Networks*, Proceeding of ACM Mobihoc USA, 2003.

[10] Li Li, Joseph Halpern, Paramvir Bahl, Yi-Min Wang and Roger Watternhofer, *A Cone-Based Distributed Topology-Control Algorithm for Wireless Multi-Hop Networks*, IEEE/ACM Trans on Networking, Vol.13, Issue 1, Feb 2005.

[11] N. Li, J. C. Hou and L. Sha, *Design and analysis of an MST-based topology control algorithm*, in Proc. IEEE INFOCOM 2003, USA, April 2003.

[12] Roger Wattenhofer, Aaron Zollinger, *XTC: A Practical Topology Control Algorithm for Ad-Hoc Networks*, Technical Report 407, Department of Computer Science, ETH Zurich, 2003.