Optimization issues and Algorithms for Wireless Sensor Networks with Mobile Sink

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1. Introduction

Wireless Sensor Networks (WSNs) are a new kind of ad-hoc wireless network that will probably bring new progress on the paradigm of pervasive computing. Many applications have already been envisioned for WSNs, such as: support for traffic engineering, providing information about traffic conditions, motor cars flows, etc; animal life monitoring and environment variables measurement, reporting values of temperature, dampness, brightness, etc.

These networks may be composed by hundreds or even thousands autonomous devices, the so called sensor nodes. Each sensor node is a low-power and constrained device, generally composed by: a processor with limited processing power; a restricted quantity of memory; a sensor board, which may contain different kinds of sensor data acquisition devices; a battery, which provides power for the sensor node work and a radio that allows wireless communication.

Given their particular features and the sensor nodes constrained resources, the WSNs have stimulated a lot of different research areas, such as low-power hardware design, routing algorithms (surveyed by [10]), topology control and optimization issues [1, 14, 15]. In general, the main aim of these researches is to extend the network lifetime, since, in the operational environment, to charge or to exchange the sensor nodes' batteries is probably an impossible/unfeasible activity. In this paper we present algorithms that address some of the problems that arise in this field:

- **Density control:** since the number of deployed sensor nodes can be really large, an important WSN aspect is density control [11, 14, 15]. In a dense network, many sensor nodes can work on the same region, generating redundant data. This is undesirable because it leads to more network traffic and increases the energy consumption [11, 14, 15]. The density control mechanism adopted prevents sensor nodes to work in the same region at the same time and ensures monitored area coverage.
- **Sink mobility:** in a WSN architecture, the sink is a special node which function is to gather the collected data and send it outside the network. Our network model does not consider a fixed sink. Nevertheless, since a WSN is expected to have a large number of sensor nodes, it could be impossible to move a sink node to each sensor communication range. However, our cluster-based approach communication will make it easy to solve this problem. Since these networks will probably have more than one cluster, we need to design efficient routes to sink tour among these clusters.

2. Related works

Density control is an important aspect of dense WSNs. Its role is to manage the WSN redundancy, in an automatic manner, keeping active only a minimum set of sensor nodes at a certain time [1]. Several centralized [1, 12] and distributed techniques [14, 15, 11] have been proposed for density control. In [12] a centralized heuristic is proposed, to divide the set of sensor nodes in mutually exclusive subsets where each subset covers the sensing area. The objective is to maximize the number of subsets. Zhang *et al.* [15] propose the an algorithm named OGDC, a distributed density control algorithm. The OGDC idea is to make the sensor nodes temporarily inactive, i.e. in sleep mode, when they are not essential to guarantee coverage and connectivity. In [11] a cross-layer design have been proposed to integrate the OGDC density control with a tree routing protocol.

Mobility have been used to improve the WSNs lifetime in a number of works [13, 7, 3, 8]. In [8, 16], sink mobility with controlled and predictable movement pattern are considered and one-hop communication is used. It has been shown that one-hop constraint imposes a large delay in the data delivery, since sensor nodes needs to wait the sink to be in its communication rage to send its data. To minimize this effect, some researches are considering multi-hop communication with mobile sink [3], reducing the sensor node waiting time.

Many papers design communication protocols to support mobility in WSN, even though little attention has been given to the motion control problem. Jea et al. [11] use a controlled mobile sink to collect data, but its trajectory is a fixed straight line, therefore the motion control is reduced to define the speed the sink will move. In [8] it is presented a sophisticated speed control; however only this part (the speed) of motion control is considered.

In many researches, like [5], clustering is proposed to hierarchical organization of WSNs' topology. This hierarchical organization leads to various improvements in WSN [5]. In a hierarchical WSN, sensor nodes only transmit data to the cluster-head, reducing the power needed to transmit; this organization way also makes easy the data aggregation and restricts the data relay in cluster-head nodes.

3. Proposed method

In this work we propose for organization of WSNs considering mobility and density control. In the first method (SHS) we use a single-hop communication strategy: sensor nodes do not relay messages from other nodes. They only receive and transmit message from/to the mobile sink, and sensor nodes can only communicate with the sink if one is in the communication range of the other. In the second method (MHS), sensor nodes are enabled to relay messages from other nodes to the sink, in a multi-hop fashion. However, the number of hops a message could cross is limited.

These methods are based upon the assumptions that each sensor node knows its geographical position, the sink knows all sensor node positions and sensor and sink communication range are fixed.

Both methods uses the same density control procedure. The role of the density control is to manage the network redundancy, keeping a minimal set of sensor nodes in activity at certain time [14]. Since sensors are not active during all the time, the network lifetime is extended. The density control is deployed to WSN by the sink, and since sink knows all sensor' positions, we could implement a centralized density control strategy. We model the density control as the weighted set cover problem (SCP) [4]: it is given a set of sensor nodes S and a set of demand points D. Each demand point $d \in D$ represents the center of a small square area in the sensing area that are covered by at least one sensor $s \in S$. Each sensor $s \in S$ has an associated activation cost w_s , which is an inverse function of the sensor node energy, to prioritize activation of sensor with more energy. Furthermore, each sensor can monitor a subset of the demand points $D_s = \{d \in D | dist(d, s) \leq C\}$, where $dist(d, s)$ is the distance between the sensor s and the demand point d and C is the sensor's sensing range. The output is a set $y_s \in Y$ of sensor nodes that are selected to be active and minimizes the sums of activation energy.

The density control solution is deployed to the WSN by our mobile sink, since it is the only node that can communicate with all sensor nodes. The density control solution is re-evaluated when each new mobile sink tour starts. The task is done when the sink queries data from the sensor: at the same moment it indicates to the sensor if it will be active in the next period. This deployment approach can lead to momentarily coverage failures. For instance, consider that sensor s^1 could be turned off in time t^1 and sensor s^2 be turned on in time $t^2 > t^1$ and sensors s^1 and s^2 have the same sensing area, i.e., $D_{s^1} = D_{s^2}$. Therefore, the subset of demand points $D^1 \subseteq D_{s^1}$ that is not in sensing area of other active sensor will be not covered in the period time $[t^1, t^2]$.

In this work we are assuming that the sensor node is able to manage its processor, its radio and the sensor board by itself. When the density control defines a sensor as active, its sensor board and processor will be turned on in the next period. The radio is always turned off after reporting data to the sink, since the radio will only be needed when sink returns.

In SHS, sink needs to be in the sensor communication range to query its data. In order to enable the single-hop communication, we divide our network in a set of clusters. Each cluster has a diameter of $2R$, where R is the sensor node communication range, supposing that R does not change during WSN operation. The algorithm used to construct clusters is based in the Minimum Spanning Tree Method, that is an agglomerative hierarchical clustering technique [6]. Given a set S of sensor nodes, this greedy algorithm starts with $|S|$ clusters of one sensor node each and successively joins the nearest clusters until no clusters could be joined because of sensor and sink communication range R restriction. This procedure produces clusters with radius up to R, what ensures that if sink is located at the cluster centroid it could communicate with all sensor nodes in the cluster since, sink and sendor node communication range is R.

In MHS, we divide the network in several trees (forest) with the property that each sensor node in the network is up to h hops of the tree root. Given a set of sensor nodes S, let X_p denote a subset of p sensor nodes and $D(y, X_p) = min_{x \in X_p} hops(y, x), \forall y \in S$, where $hops(y, x)$ is the minimum distance beteween x and y sensor nodes. Finally, let $H(X_p) = max_{y \in S} D(y, X_p)$. The trees are constructed by solving the optimization problem $p_\lambda = min\{p : X_p \subseteq S, H(X_h) \leq \lambda, h \geq 0\}$, the inverse p-Center problem [9]. This modeling strategy minimizes the number of trees, what reduces the sink tour length, compared to the SHS method. Since the sink speed is orders of magnitude lower than wireless comunication speed, this minimization could produces WSN with lower message delay than SHS. The inverse p-Center problem is commonly solved by a reduction to the minimum set cover problem. Given a graph representation G of the WSN, we construct a matrix A where a_{ij} is 1 if the sensor $i \in S$ has a path in G to sensor $j \in S$ within λ hops and 0 otherwise. The X_p is obtained by soving the optimization problem (set cover problem) $X_P = min\{k : \; x_k = 1, \; \sum a_{ik} x_k \geq 1 \; \forall i, \;\; x_k \in \{0, 1\}\}$.

Both methods divide the sensor nodes S in disjoint subsets, and sink needs to visit each subset to collect data. In the SHS approach, the sink needs to be in the cluster centroid, and in MHS sink needs to be in the tree root to collect data. Designing efficient routes to move the sink toward subsets is a challenger problem in our model. It has strong impact in some WSN important metrics like message delay and successful message delivery rate. The mobile sink needs to visit each subset in such a way that minimizes the message lost in sensor buffers and minimizes the message delay.

The major disadvantage of using a mobile sink is that there will be considerable delay in acquiring sensed data, since a node need to wait for the sink to approach it. Moreover, if the time that one sensor waits for the sink is too large, some data will be dropped from its buffer to accommodate new one. Therefore, design routes to move sink is an important part of this work. We model the problem of design route to sink as the classical Travelling Salesman Problem (TSP) [2] to both method. Each subset is modelled as one TSP city and the Euclidian distance between the clusters center is used as the TSP distance measurement.

Now we detail the integration of these components into one method for WSN optimization. In the beginning of the WSN operation, the sink defines the clusters (SHS mode) or defines the trees (MHS mode) and designs the route toward these clusters/trees. After this procedure, it starts the tour over the clusters/trees.

The first task in a new tour is to solve the density control problem to select the subset of sensor nodes that will be active in the next tour. After this setup, the sink starts moving to the first cluster/tree in the tour in order of gathering sensor nodes data. Each time sink visit a cluster/tree, each sensor nodes in this cluster/tree turn its radio on to communicate with the sink. First of all, the sink sends the density control decision to all sensor nodes in the cluster/tree, after this, the sensor nodes start to send its data to the sink. When the sink finishes reading all sensor nodes, it moves to the next one. After send its data to the sink, each sensor node turns off its radio and if it is not used in the coverage in the next tour (density control decision), it turns off its sensor boarding and processor.

4. Results

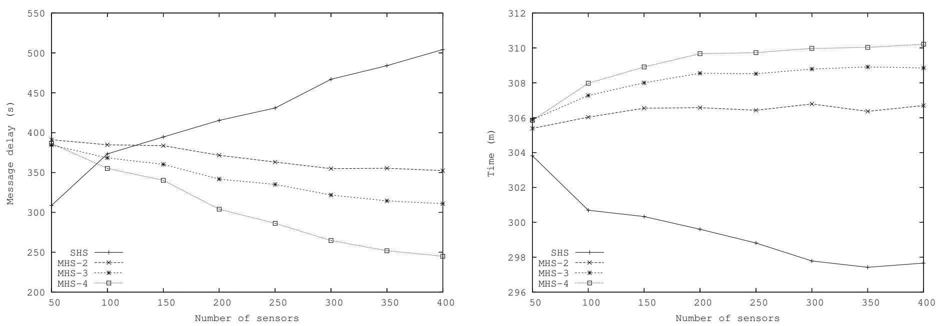
We evaluate our proposed method through simulation. We used a WSN simulator constructed over the SWANS simulator [1]. The simulation parameters were chosen based on the hardware of Mica2 nodes[2], which are commercially available.

In this paper, all optimization problems are solved using mathematical programming model. In this WSN configuration, the TSP is solved up to 10 cities and the SCP is solved up to 400 sub-sets. These problems is solved in no more than one minute by CPLEX solver, wich we consider acceptable in WSN context.

The simulation experiments were designed to allow a comparative analysis of the network delay, reliability and coverage. The results show the comparison between three configurations of our proposed method and one WSN with a tree routing protocol, described as follows: **RT** - Implements the tree routing algorithm [11] with routing tree updated every 100s; **SHS** - Implements the SHS method; **MHS-2** - Implements the MHS method where $\lambda = 2$; **MHS-3** - Implements the MHS method where $\lambda = 3$; and **MHS-4** - Implements the MHS method where $\lambda = 4$.

Unless stated, the simulation parameters used are: Sensing area = 40000 m^2; Sensor energy = 50 mAh; Sensing range = 15 m; Communication range = 30 m; Transmission power = 8.9 mA; Reception power = 7 mA; Radio idle power = 7 mA; Processor power = 8 mA; Data acquisition board power = 5 mA; and Sink speed = 1 m/s.

A temperature monitoring application was chosen to be simulated. In this application, sensor nodes collect the temperature periodically at a constant rate of 1/20 Hz. Each temperature measure has 32 bits of information. The sensor node memory can store 4 Kbytes, which is sufficient to support 14 hours of sensor data collection. The MAC layer was the IEEE 802.11 available in SWANS simulator, as the Mica2 nodes implements a CSMA/CA protocol. All simulation experiments were executed for 10 hours and repeated 33 times. The results present confidence interval of 95%.



(a) Delay versus number of sensors. (b) Time of dead of the first sensor.

Figure 1:

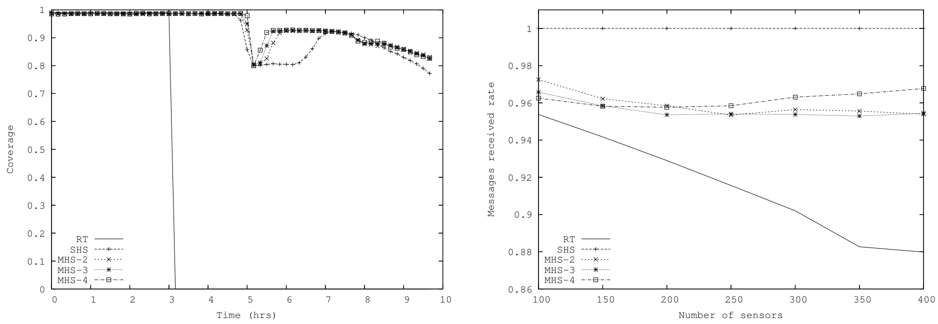
The main disadvantage of using a mobile sink is the large message delay [13]. We analyse the different configurations performance as the size of the network grows. Figure 1(a) shows the results. We do not show in this figure the RT results, since they are orders of magnitude lower than the other configurations; however RT message delay increases 4.9 times (from 0.1s to 0.6s) when the network grows from 50 to 400 sensor

[1]Scalable Wireless Ad hoc Network Simulation. http://jist.ece.cornell.edu/

[2]XBOW MICA2 - Wireless Measurement System. http://www.xbow.com/

nodes. In the same interval, SHS message delay increases only 0.6 times, while SHS configurations reduces the message delay up to 0.37 times (MHS-4). This result shows the greater advantage of RT in delay metric, however shows the better scalability of MSH and SHS methods.

Now we analyse the algorithms in terms of network lifetime. The network lifetime is commonly defined as the time of the first sensor run out of energy. Figure 1(b) shows the results. Here, again, we do not show the RT resutls, since the WSN with RT configuration lifetime do not have considerable changes when network grows: It presents an average lifetime of 192s (standard deviation=0.82). The SHS method decreases its performance as the network grows. Since in this configuration message relay is not allowed, sink has a larger tour length than MHS and this reduces the lifetime in SHS method due to large cicle period. In average, the MHS-4 is 60% better than RT configuration.



(a) Network coverage.

(b) Message delivery rate.

Figure 2:

Lifetime as defined previously is not a good metric for estimate the WSN useful life. In a dense network, a failure of some sensor nodes could not compromise the WSN coverage or some coverage failures could be acceptable. For instance, we analyse network covarage along the time for a 400 nodes sensor network. As Figure 2(a) shows, our methods improves significantly the network coverage. As the radio idle energy consumption and the processor energy consumption is the major component of the energy consumption, the configurations that do not make density control (RT) perform worse than the others. RT configuration is able to maintain more than 80% of coverage up to 3 hours, while our methods keep more than 80% of coverage up to 9 hours.

The success message delivery rate is another important metric of every network protocol. Figure 2(b) shows the rate of messages received by the sink as network size grows. As SHS use a single hop communication protocol based on a time division multiplexing (TDM) coordinated by the mobile sink, we do not have message collision, therefore, in this configuration, messages are only lost by sensor nodes failures (run out of energy). Since in our simulation a few number of sensor nodes die in SHS method, the message received rate is close to 1. All other configurations has message collision, therefore this configuration performe worse than SHS. As network grows, message received rate reduces in RT configuration, as expected, since in this configuration messages could cross large number of hops increasing the collision probability. The MHS method, however, has a limited path lengh what reduces the collision probability compare to RT. This method produces WSN configuration less sensible to network size grows.

5. Conclusions and Future works

In this paper we present two new methods for the organization of WSNs, which integrate density control and sink mobility. In our integrated methods, the WSN is logically organized in clusters or trees, to reduce the sink tour time. Furthermore, the density control decisions are deployed to sensor nodes by the sink node. The simulation results show that our method is promising to extend WSN lifetime. Furthermore, as previewed in the literature, our simulations do show a large message delay using mobile sink, but this large delay is acceptable for a large number of WSN applications. However, our results show that our methods could improve the network coverage for a period larger than methods using data forwarding. Considering a upper bound of 80% of coverage, our methods increase the WSN operation time up to 2 times. As future work direction we want to investigate some strategies to reduce the message delay, for instance, by using more than one mobile sink.

References

[1] M. Cardei, D. Maccallum, M. Cheng, M. Min, X. Jia, D. Li, and D. Du. Wireless sensor networks with energy efficient organization. *Journal of Interconnection Networks*, 3(3-4):213–229, 2002.

[2] R. Dantzig, R. Fulkerson, and S. Johnson. Solution of a large-scale traveling-salesman problem. *Operations Research*, 2:393–410, 1954.

[3] S. Gandham, M. Dawande, R. Prakash, and S. Venkatesan. Energy efficient schemes for wireless sensor networks with multiple mobile base stations. In *IEEE GLOBECOM*, San Fransisco, USA, December 2003.

[4] M.R. Garey and D. S. Jonhson. *Computers and Intractability: A Guide to the Theory of NP-Completeness*. W H Freeman, 1979.

[5] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan. An application-specific protocol architecture for. *IEEE Trans. on Wireless Communications*, 1(4):660–670, 2002.

[6] R. Jain. *The Art of Computer Systems Performance Analysis: Techniques for Experimental Design, Measurement, Simulation, and Modeling*. John Wiley and Sons, 1991.

[7] D. Jea, A. Somasundara, and M. Srivastava. Multiple controlled mobile elements (data mules) for data collection in sensor networks. In *IEEE/ACM Intl. Conf. on Distributed Computing in Sensor Systems*, 2005.

[8] A. Kansal, A. Somasundara, D. Jea, M. Srivastava, and D. Estrin. Intelligent fluid infrastructure for embedded networks. In *MobiSys '04*, pages 111–124, New York, NY, USA, 2004. ACM Press.

[9] P. Mirchandani and R. Francis. *Discrete Location Theory*. John Wiley and Sons, 1990.

[10] R. Rajaraman. Topology control and routing in ad hoc networks: a survey. *SIGACT News*, 33(2):60–73, 2002.

[11] I. Siqueira, M. Fiqueiredo, A. Loureiro, J. Nogueira, and L. Ruiz. An integrated approach for density control and routing in wireless sensor networks. In *Parallel and Distributed Processing Symposium*, pages 10–19, Greece, April 2006.

[12] S. Slijepcevic and M. Potkonjak. Power efficient organization of wireless sensor networks. In *IEEE Intl. Conference on Communications*, volume 2, pages 472–476, Helsinki, Finland, 2001.

[13] W. Wang, V. Srinivasan, and K. Chua. Using mobile relays to prolong the lifetime of wireless sensor networks. In *MobiCom '05*, pages 270–283, New York, NY, USA, 2005. ACM Press.

[14] F. Ye, G. Zhong, S. Lu, and L. Zhang. Peas: A robust energy conserving protocol for long-lived sensor networks. In *ICNP '02: Proc. of the 10th IEEE Intl. Conf. on Network Protocols*, pages 200–201, Washington, DC, USA, 2002. IEEE Computer Society.

[15] H. Zhang and J. C. Hou. Maintaining sensing coverage and connectivity in large sensor networks. *Intl. Journal of Wireless Ad Hoc and Sensor Networks*, 1(1-2):89–124, 2005.

[16] W. Zhao, M. Ammar, and E. Zegura. A message ferrying approach for data delivery in sparse mobile ad hoc networks. In *MobiHoc '04*, pages 187–198, New York, NY, USA, 2004. ACM Press.