TRAT: TRaffic-Aware Topology Control Algorithm for Energy Efficiency in Wireless Sensor Networks

Yeonsu Jung, Junghyo Kim and Yunju Baek
Department of Computer Science and Engineering,
Pusan National University, Busan 609-735, South Korea
{Yeonsu, Yunju}@pusan.ac.kr, jhkim@juno.cs.pusan.ac.kr

ABSTRACT
In wireless sensor networks, a number of nodes deployed in dense manner should be self-configured to establish the topology that provides communication and sensing coverage under stringent energy constraints. To establish an efficient topology, we propose the TRaffic-Aware Topology control (TRAT) algorithm that reduces energy consumption by considering the total amount of data flows in the network. Our algorithm controls the number of active nodes and adjusts nodal transmission power with traffic information. According to our results, the proposed algorithm shows about a 30% better performance than other methods in terms of energy efficiency.

Categories and Subject Descriptors
C.2.1 [Computer-Communication Networks]: Network Architecture and Design—Network topology; C.2.2 [Computer-Communication Networks]: Network Protocols

General Terms
Algorithms, Performance, Design, Experimentation.

Keywords
Wireless sensor network, topology control, sleep management, data rate, network lifetime.

1. INTRODUCTION
Wireless sensor networks are composed of a large number of nodes with computation, wireless communication and sensing capabilities. Nodes in dense wireless sensor networks coordinate to perform distributed sensing tasks. A node is powered by an internal source such as a battery and has a limited communication capability. In addition, a large number of nodes deployed in dense networks will preclude manual configuration. Therefore, nodes have to self-configure to establish the topology that prolongs the sensor network lifetime and improves the efficiency of data transmission.

Related research for energy efficiency in wireless sensor networks is classified into three groups as follows: topology control, sleep management and energy-aware routing. The topology control approach adjusts nodal transmission power to reduce energy consumption while preserving necessary network connectivity. Sleep management turns off redundant nodes and decreases the number of nodes that forward data using multi-hop transmission. Energy-aware routing protocols consider energy efficiency in order to choose a routing path. To maximize energy efficiency for wireless sensor networks, all approaches topology control, sleep management and energy-aware routing methods have to be integrated. However, this integration demands centralized computation and global information including node location. This centralized method is not suitable for wireless sensor network systems.

Therefore, we propose a distributed approach which integrates topology control and sleep management. TRAT aims to reduce energy consumption by considering the total amount of network flows. It controls the number of active nodes and adjusts nodal transmission power with information about network flows.

The remainder of this paper is structured as follows. In section 2, topology control and sleep management are discussed as they relate to this work and the motivation for it. Section 3 describes the basic concept of the proposed topology control protocol. Section 4 demonstrates TRAT and section 5 includes the performance evaluation of the proposed scheme. Finally we conclude this paper in section 6.

2. Related works and motivation
We review several representative topology control methods and sleep management protocols. However, the energy-aware routing approach is not considered in this paper.

Topology control methods adjust nodal transmission power in order to reduce energy consumption while preserving the desirable properties of wireless networks. LMST [6] is the Minimum Spanning Tree (MST)-based topology control algorithm. LMST establishes a minimum spanning tree preserving 1-connectivity by using local information. Li et al modified LMST protocol so as to preserve k-connectivity and proposed $FLSS_k$ [7]. $FLSS_k$ is a strictly localized algorithm that minimizes the maximum transmission power. LINT and LILT [8] use two distributed heuristic methods to adaptively adjust the transmission power of the node in response to the changes of a topology. LINT uses local neighborhood information and LILT exploits global topology information.

Sleep management methods turn off redundant nodes that are deployed at similar geographical location. In this approach, some nodes remain in an active state in order to deliver data continuously, while the other nodes are in a sleep state. The representative sleep management algorithms are GAF [9], ASCENT [1], SPAN [2] and EDP [5]. Each algorithm uses different reference values. GAF identifies redundant nodes according to the geographical location of the nodes and controls the duty cycle of the nodes in order to extend the lifetime of the network. ASCENT determines the role of the node based on the link quality. EDP considers the remaining energy of each node. SPAN chooses the coordinators that consist of a backbone. Periodically, a non-coordinator node checks the eligibility rule in order to decide if it should become a coordinator or not. The eligibility rule is as follows: if two neighbors of a non-coordinator node cannot reach each other, either directly or via one or two coordinators, the node should become a coordinator. The eligibility rule can ensure that enough coordinators operate in the entire network.

Yin et al [4] proposed a method which integrates topology control and sleep management. This approach applies the SPAN algorithm to establish a sparse backbone. Subsequently it adjusts the transmission range of the active nodes using a topology control protocol such as a neighborhood shortest path algorithm. MPCP [3] considers the data rate of sources and integrates topology control, sleep management and the energy aware routing method. First, MPCP determines the energy efficient routing path and makes the nodes on the path work in the active mode. It adjusts the transmission range of the active nodes for energy efficiency and puts the other nodes into a sleep state.

Table 1. The parameter used in corresponding protocols.

Protocol	Used parameters
GAF [9]	Geographical position, remain energy
ASCENT [1]	Data loss rate
SPAN [2]	Remain energy, utility
EDP [5]	Remain energy

Previous research considered many factors including the remaining energy, the number of neighbors, the packet loss rate and so on. However, the data rate of sources was not considered although it can significantly affect energy efficiency for wireless sensor networks. MPCP considered this parameter but the dependency on the routing protocol is too high. So we propose the traffic-aware topology control algorithm for wireless sensor networks that reduces energy consumption.

3. The basic concept

In this section, we describe the correlation between the total amount of data flow and energy efficiency in wireless sensor networks. Since wireless communication dominates the energy consumption of a node, conserving the energy to be consumed by a radio transceiver is an important issue. Generally, a radio transceiver has four operating modes: transmit, receive, idle and sleep. The quantity of energy to be used by the radio transceiver is different according to the operation modes. The amount of energy consumption is represented by $P_{tx}(d)$, P_{rx}, P_{id} and P_s, where d is the Euclidean distance of the transmission.

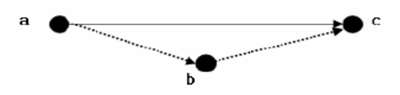

Figure 1. Two communication paths from *a* to *c*. : a → c or a → b → c.

As shown in Figure 1, suppose that a simple wireless sensor network consist of three nodes. The data rate of all nodes is B bps and node *a* sends to *c* at a data rate of R bps. There are two communication paths. Node *a* can deliver packets directly to *c* using the transmission range |*ac*| while node *b* is sleeping. Node *a* can send data through *b*. In these cases, the total power consumption can be computed as follows:

$$P1 = \frac{R}{B} \times P_{tx}(|ac|) + \frac{R}{B} \times P_{rx} + 2\left(1 - \frac{R}{B}\right) \times P_{id} + P_s \quad (1)$$

$$P2 = \frac{R}{B} \times \{P_{tx}(|ab|) + P_{tx}(|bc|)\} + \frac{2R}{B} \times P_{rx} + \left(3 - \frac{4R}{B}\right) \times P_{id} \quad (2)$$

P1 is energy consumption when node *a* communicates with *c* directly and P2 is that in the other case. Equation (1), (2) can be plotted as Figure 2. The energy efficiency of the wireless network depends on the data rate threshold R_0. P2 is larger than P1 if the data rate is less than the threshold R_0. In the other case, P2 is smaller than P1. R_0 can be computed by (3) and is dependent upon the radio energy model.

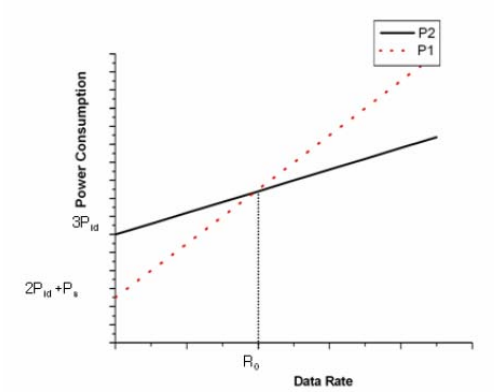

Figure 2. The power consumption as a function of data rate.

$$R_0 = \frac{P_{id} - P_s}{P_{tx}(|ac|) - P_{tx}(|bc|) - P_{tx}(|ab|) + 2P_{id} - P_{rx}} \quad (3)$$

We can utilize this fact to reduce energy consumption in a large network which is composed of more sensor nodes. If the current data rate of sources is relatively low, decreasing the number of active nodes and increasing the nodal transmission power help to improve energy efficiency. As shown in equation (1) and (2), when R is small, the ratio of energy dissipation by the transmission to total energy consumption is low. Therefore, the increment of the energy which is consumed by transmission is less than the increment of the energy which is preserved by decreasing the number of active nodes. On the contrary, increasing the number of active nodes and reducing nodal transmission power help to conserve energy if R is high.

4. TRAT: the Traffic-Aware Topology control protocol

The traffic-aware topology control for wireless sensor networks has the following assumptions. Sensor nodes are sufficiently deployed in the sensor field. Each node knows its own id and can adjust its own transmission range. Also nodes are globally time-synchronized. TRAT aims to prolong the network lifetime in a special applications. Each source sends data to the sink at a fixed data rate during a predetermined period. After this period, each source sends data at different data rates. The gap between the data rate in previous rounds and in the current round is significant. The algorithm works in four phases. Operations of the protocol are detailed as follows: traffic discovery, sleep management, topology control and data forwarding.

1st phase, traffic discovery: Each node calculates Active Node Density (*AND*) as in equation (4). α stands for sensitivity on the amount of data and β is the minimum value of *AND*. These values are predetermined.

$$AND = \alpha \times \text{amount of data in previous round} + \beta \qquad (4)$$

2nd phase, sleep management: each node makes a decision on whether to sleep, or to forward data from the sources to the sink exploiting *AND* and the delay value.

Step 1: Each node determines the *delay* by equation (5). The *delay* depends on the remaining energy of each node. The node with more energy has a small *delay*. Thus the possibility that the node with more energy remains active is relatively high. E_r means the remaining energy and E_i stands for initial energy of a node.

$$Delay = (1 - E_r / E_i) \qquad (5)$$

Step 2: Each node receives a *Node_Hello* message from the other nodes until its own *delay* is fired or the number of received *Node_Hello* messages is more than *AND*. Nodes record the node id and the location of the node as neighbor information when every *Node_Hello* message is received. The node whose delay is fired broadcasts a *Node_Hello* message, including the node id and location information. The node operates continuously in active modes. If not, the node works in the sleep mode.

3rd phase, topology control: each active node adjusts its own transmission range in the phase. Since LMST is a localized algorithm and demands only local information, we applied the LMST algorithm.

4th phase, data forwarding: active nodes forward data from the sources to the sink. Each active node stores the data traffic information including the source id and the data rate of every packet received.

5. Performance Evaluation of TRAT

In order to evaluate the performance of the proposed algorithm, we established a simulation model in the NESLsim [10] based on the PARSEC platform. PARSEC (PARallel Simulation Environment for Complex systems) is a C-based discrete-event simulation language.

5.1 Simulation Environment

1000 sensor nodes were deployed in a uniformly random fashion over a sensor field size of 700x700. The maximum transmission range of each node is 100 and the data rate is 40k bps. A sink was located at (350, 350) and twenty sources were deployed at the border of the field. Table 2 shows the radio energy model. The energy used for transmission is much more than that in other operation states and depends on the transmission distance d.

Table 2. The energy consumption model of a radio transceiver.

Tx	Rx	Idle	Sleep
$6 \times (d/d_{max})^2$W	25mW	24mW	6uW

Table 3. The parameters of four models.

Model	Number of active nodes	Number of sleep nodes	Transmission power
Model LH	50	950	100
Model MM	70	930	70
Model HM	110	890	45
Model HL	170	830	30

We evaluated the performance of the proposed protocol by comparing to four models. Model LH had a low number of active nodes with a high average transmission range. Model MM represented the two parameters with relatively medium values. There were more active nodes in model HM and the average transmission range of active nodes was 45. Finally model HL had more active nodes and had the least number of sleep nodes. The parameters of each model are represented in table 3. Each active node forwarded data to a sink using a minimum hop routing scheme. This scheme determined the routing path in order to minimize the number of hops from the sources to the sink.

5.2 Simulation Result

We evaluated the total power consumption of four models and TRAT as a function of the data rate. Figure 3 shows the power consumption of each model as a function of the data rate. Since only 50 nodes remained active in model LH, undesirable energy consumption for idle listening was low. The energy dissipation of model LH was the lowest when the packet size was 20bits. But this energy consumption dramatically increased with the increment of the data rate because each active node had a large transmission range. On the contrary, model HL had more active nodes and had a lower nodal transmission ranges. In this model, the energy dissipation was more compared to that of the other models at 20 packet size. If the more traffic is generated, the model has better energy efficiency comparing to the other models. Figure 3 shows that TRAT adaptively controls the number of active nodes and adjusts the nodal transmission range in response to the changes of the data rate. The performance is similar to the minimum energy consumption of the four models at each data rate.

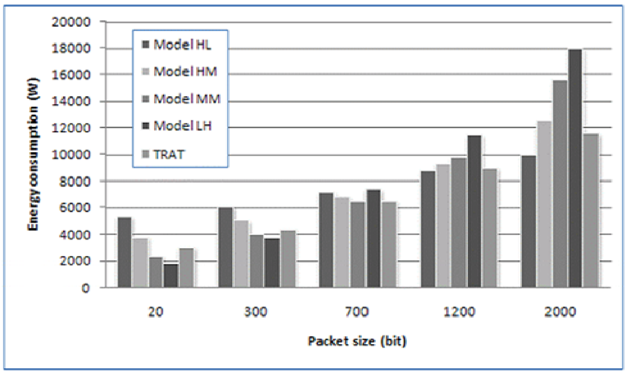

Figure 3. Power consumption of each model as a function of the data rate.

Figure 4 shows network topologies that were established by TRAT as a function of the data rate. Our algorithm controls the number of active nodes with the total amount of current traffic.

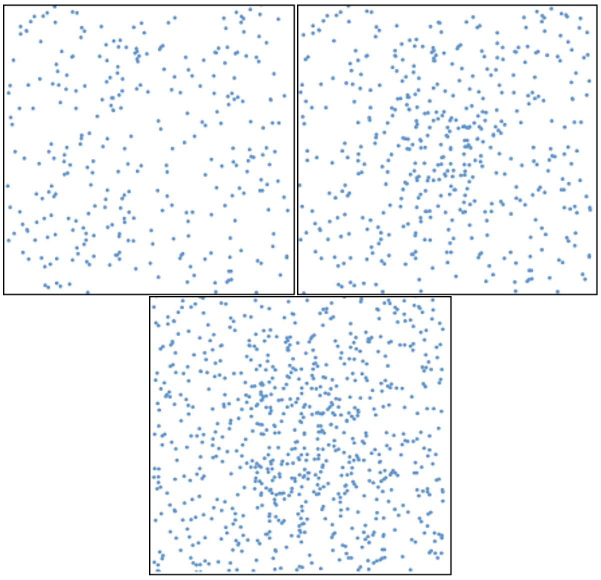

Figure 4. Network topologies as a function of data rate under our protocol.

We applied our protocol from section 4 to a described application in section 4. The data rate of the sources was varied from 20 to 4,000. The period was 10s and the simulation operated for 60 rounds. Table 5 represents the total energy dissipation of each model. The performance of TRAT was 40% better compared to that of model LH. The energy consumption of TRAT was 30% lower than the other models.

Table 4. Energy consumption of TRAT and four models.

Model	Energy consumption (W)	Efficiency (%)
Model LH	7,180	79.52
Model MM	7,421	76.94
Model HM	7,708	74.08
Model HL	8,848	65.53
TRAT	5,709	100

We evaluated the performance of TRAT compared to EDP and EDP-LMST. The initial energy of each node was 5W and the time of each round was 1s. The entire running time was 500 rounds. Figure 5 depicts the network lifetime of each algorithm as a function of the data rate. EDP-45 means that the transmission range of nodes is 45. EDP-LMST stands for the algorithm that integrates EDP and LMST. The performance of EDP-45 was the worst. All nodes were active initially in the EDP, but the transmission range was too small. Therefore the nodes located around the sink ran out of energy. The performance of EDP-LMST was better than that of EPD-45 because EDP-LMST adjusted the nodal transmission power. The network lifetime in TRAT improved by 20% compared to that of the other algorithms. Figure 6 shows the average energy consumption of each algorithm. The energy consumption of EDP is more than EDP-LMST and TRAT. The performance of TRAT was better by about 20% in terms of energy efficiency.

We applied our protocol from section 4 in order to compare with the other protocols. The performance of EDP-45 and EDP-70 was low. EDP-100 consumed more energy than EDP-45 and EDP-70. But EDP-100 had a longer lifetime than the others. The reason for this result was due to the long transmission range. The performance of TRAT showed an improvement of about 20% in terms of energy efficiency and lifetime.

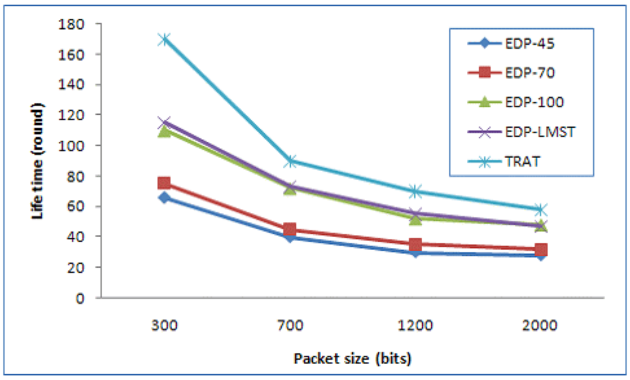

Figure 5. Network lifetime of each protocol as a function of the data rate.

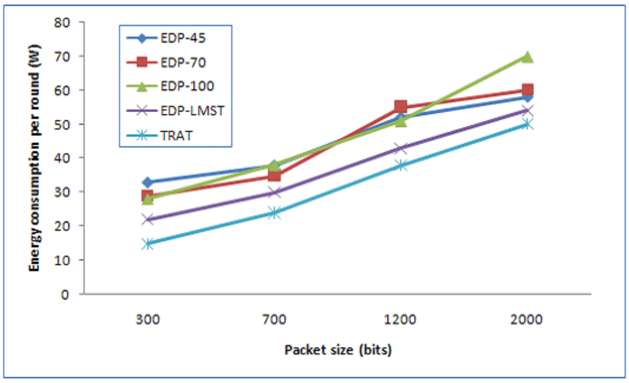

Figure 6. Network lifetime of each protocol as a function of data rate.

Table 5. Energy consumption of TRAT and the others in the specific application.

Algorithm	Energy consumption (W)	Efficiency (%)	Lifetime (round)
EDP-45	46.09	78.63	26
EDP-70	42.22	85.84	33
EDP-100	49.83	72.73	49
EDP-LMST	45.74	79.23	51
TRAT	36.24	100	62

6. Conclusion

This paper proposes the Traffic-Aware Topology Control (TRAT) algorithm that reduces energy dissipation. Unlike other topology control protocols, TRAT considers the total amount of data flow in the network in order to control the number of active nodes and adjust nodal transmission power. We described the correlation between energy efficiency and the total amount of data flow, and we implemented TRAT to evaluate its performance. The simulation results show that the energy efficiency of the proposed protocol improved by about 30% compared to that of the static models and was better than that of EDP and EDP-LMST. In future, we would like to undertake an experiment on the performance of TRAT in a real life environment and apply the TRAT algorithm to a real life application.

7. ACKNOWLEDGMENTS

"This work was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD)" (The Regional Research Universities Program/Research Center for Logistics Information Technology)

8. REFERENCES

[1] A Cerpa, D Estrin. ASCENT: Adaptive Self-Configuring sEnsor Networks Topologies. Mobile Computing, IEEE Transactions on Volume 3, Issue 3, pp. 272 – 285 (2004).

[2] Benjie Chen, Kyle Jamieson, Hari Balakrish-nan, Robert Morris. Span: An energy-efficient coordination algorithm for topology maintenance in Ad Hoc wireless networks. In Proceedings of the 7th annual ACM international conference on Mobile computing and networking, pp.85-96 (2001).

[3] Guoliang Xing, Chenyang Lu, Ying Zhang, Qingfeng Huang, Robert Pless. Sensor networks: Minimum power configuration in wireless sensor networks. In Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing MobiHoc (2005).

[4] Hongchi Shi, and Yi Shang. A Two Level Strategy for Topology Control in Wireless Sensor Networks. Parallel and Distributed Systems, 2005. In Proceedings 11th International Conference on Volume 2, pp.358 – 362 (2005).

[5] Marc R. Pearlman, Jing Deng, Ben Liang, Zygmunt J. Haas. Elective Participation in Ad Hoc Networks Based on Energy Consumption. Global Telecommunications Conference, 2002. GLOBECOM '02. IEEE Volume 1, pp.26 – 31 (2002).

[6] N. Li, J. C. Hou, and L. Sha. Design and analysis of an MST-based topology control algorithm. Proc. IEEE INFOCOM 2003, vol. 3, pp. 1702–1712 (2003).

[7] Ning Li, Jennifer C. Hou. Localized Fault-Tolerant Topology Control in Wireless Ad Hoc Networks. IEEE Transactions on Parallel and Distributed Systems, vol.17, no.4, pp. 307-320 (2006).

[8] R. Ramanathan and R. Hain. Topology control of multihop wireless networks using transmit power adjustment. Proc. IEEE INFOCOM 2000, vol 2. pp. 404-413 (2000).

[9] Ya Xu, John Heidemann. Geography informed Energy Conservation for Ad Hoc Routing. In Proceedings of the Seventh Annual ACM/IEEE International Conference on Mobile Computing and Networking (2001).

[10] NESLsim, http://www.ee.ucla.edu/~saurabh/NESLsim/