Proceedings of APCC2008 copyright © 2008 IEICE 08 SB 0083

A Robust and Energy Efficient Global Gradient Setup Mechanism for Gradient Based Routing in Wireless Sensor Networks

Shah Nawaz Khan
GIK Institute of Engineering
Sciences & Technology, Topi
shahnawaz@giki.edu.pk

Noor M. Khan
Muhammad Ali Jinnah University
Blue Area, Islamabad
noor@ieee.org

Mushtaq Ahmed
GIK Institute of Engineering
Sciences & Technology, Topi
mushtaq@giki.edu.pk

***Abstract*- Gradient based routing protocols are a major part of the research in protocols for Wireless Sensor Networks. The actual performance of these protocols in real scenarios is dependent on the efficient setup and maintenance of the global gradient. The 'cost-field' is one such global gradient. The network wide cost-field allows the nodes to communicate with the sink without maintaining specific routing information or global/local node identification. All the converge-cast communication in the network follows this cost-field implicitly with least routing overhead. In this paper we propose a new energy efficient and dynamic solution to cost-based global gradient setup for gradient based routing protocols in wireless sensor networks. Our proposed mechanism extends previous work in [10] and develops a more dynamic solution. Simulation results show that our proposed mechanism is energy efficient as it requires only one broadcast per node to establish the cost field and is also robust to changing network conditions.**

I. INTRODUCTION

The consistent development and progress in the fields of low-power micro electronics, small scale radios and sensor technology have paved the way for the development of small and relatively inexpensive sensor nodes that can communicate through wireless medium to form a wireless sensor network [1]. Such an unattended network of small and capable sensor nodes opens up several new application areas such as disaster relief, military surveillance, habitat monitoring [8], intelligent structures, etc.

Sensor nodes usually have very limited energy resources for sensing, communication and processing of data, which are their three most common operations [6]. Among these communication is the most expensive operation in terms of energy consumption. According to a comparison presented in [5], the cost of transmitting one bit over 100m is equal to the cost of executing 3000 instructions. This is the major reason why energy efficiency has been the most important aspect of all the research in the area of wireless sensor networks and avoiding unnecessary communication a main objective for the purpose. Energy harvesting for the physically small nodes of wireless sensor networks is a possibility but has not matured enough to be readily used.

A large number of routing protocols for wireless sensor networks are based on the establishment of a cost based global gradient around the sink [11, 7, 4]. Such a cost-field provides implicit routing information for all in-network converge-cast communication by implicitly directing the communication towards the sink. The other advantage of having such implicit routing information is that the nodes do not need to maintain global/local identification and hence they also have lesser memory requirements.

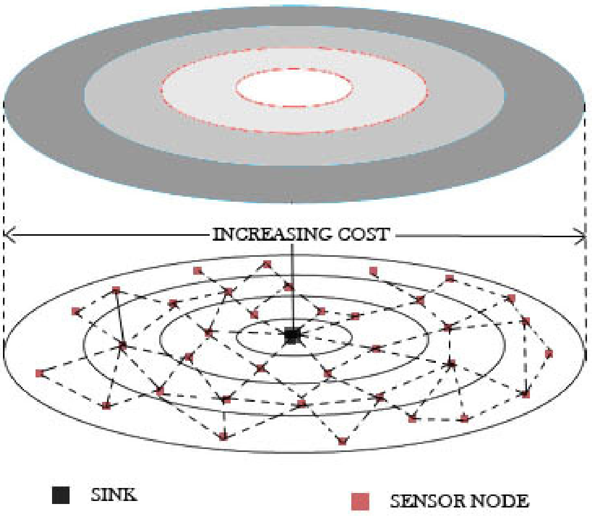

Figure 1. Larger circles represent larger cost

In this paper we present a new dynamic and robust cost based global gradient setup mechanism that is not only energy efficient but also robust to changing network conditions. Our proposed mechanism ensures that the cost-field is set around the sink in least number of broadcasts during the setup phase and in a time based incremental way. We develop our mechanism keeping in view the propagation, communication and processing delays present in the wireless sensor networks.

The rest of the paper is organized as follows. In section II we discuss related work followed by an introduction to cost-field concept and minimum cost path forwarding in section III. In section IV we discuss our proposed mechanism in detail followed by simulations and results using OMNET++ [3] in section V. We conclude the paper in section VI.

II. RELATED WORK

Gradient based routing is an active area of research and a number of gradient based routing protocols have been proposed already [11, 5, 7, 4]. All such gradient based protocols maintain some form of network-wide global gradient while some also maintain local gradients for data aggregation or for mobility compensation [9]. In [10], the authors have proposed a novel back-off based cost-field setup algorithm what finds the optimal costs of all nodes to the sink with one single broadcast message overhead. Their proposed algorithm although quite efficient for static scenarios is not dynamic and hence not robust to changing network conditions.

In [11], the authors present a gradient based robust data delivery protocol that builds upon their earlier work presented in [10]. Their proposed protocol achieves high reliability in large scale sensor network with fallible wireless links and unreliable sensor nodes but with proportionately higher energy costs.

In [7], the authors propose the spreading of traffic across the entire sensor network uniformly based on the established cost based gradient for the uniform consumption of network energy resulting in extended network life-time.

III. COST FIELD CONCEPT & MINIMUM COST PATH FORWARDING

The cost-field concept is similar to the natural phenomena of height or altitude. An object with a high altitude will fall towards a lower altitude when free [10]. Similarly the cost-field is a global gradient of increasing cost from the sink towards the outer nodes as depicted in Fig. 1. This gradient is implicitly followed by in-network communication whenever a source node wants to send data to the sink.

The cost-field setup is initialized by the sink and is expanded further by its neighbors. During the cost-field setup each node gets several packets from its neighbors containing different communication cost with the sink along different paths. Every node chooses the least costly path to the sink and only stores that least cost value.

If we consider hop count to be the communication cost, Fig. 2 shows the cost values of different nodes for communication with the sink. In Fig. 2, node 'D' has the highest number of neighbors and hence it receives several cost-packets from its neighbors containing different hop counts each representing different path. Node 'D' however, has the minimum hop count of 2, which becomes its minimum cost 'MC' during cost-field establishment.

When a source wants to send data to the sink, it assigns its minimum cost of reaching the sink to all packets and broadcasts the packets as in [11]. Every node then makes an independent decision of forwarding the packets further or dropping them based on the cost values in the packets. Every packet contains the minimum cost of reaching the sink and the cost consumed so far. The nodes do not need to maintain any global or local IDs since the routing is data driven. The data can also travel through multiple paths when a source assigns a higher cost to the packets that its minimum cost MC, which improves the reliability of data transmission as proposed in [11].

Wireless sensor networks are dynamic in many aspects. The topology of the network may change considerably due to node and channel failures, new nodes added to the network, changing environment, etc. This requires that the cost-field be refreshed after some period of time so that the newly arose conditions are dealt with accordingly. The idea proposed in [10] works fairly well for static environment with low topological changes but has shortcomings when used in highly dynamic and vulnerable sensor network environments since it does not provide a dynamic solution.

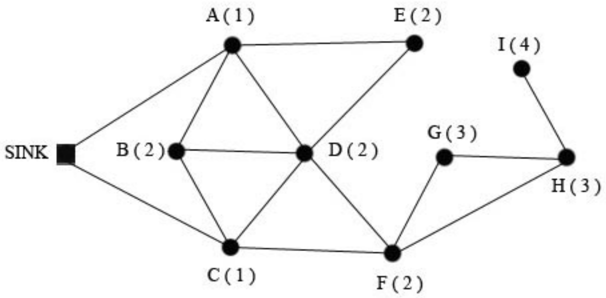

Figure 2. Each node only stores the minimum hop-count to reach the sink

IV. PROPOSED MECHANISM

A. Overview

The easiest solution of establishing a cost field is through flooding of the entire network where a node broadcasts its minimum cost to other neighbors as soon as it receives a new lower cost value. The 'cost' can take many forms depending upon the application primarily. For example in a surveillance application the data arrival time is more important than the energy consumed to transmit that data, hence the packet arrival delay from source to destination becomes the cost. For other applications energy consumption, hop count, etc may become 'cost' for the global gradient. Initially all the nodes have a cost of ∞ and hence the first cost-packet received by all nodes results in a new minimum cost 'MC' and therefore in first broadcast. We call this cost-packet an ADV packet. If the node later receives ADV packets from other neighbor nodes which lead to a new smaller cost, the node broadcasts again.

The flooding mechanism is very energy inefficient since most of the nodes make more than one broadcasts before getting the ADV packet through the minimum cost path. For example, a network covering 150 x 150 square meter area and having 1500 nodes of 10m transmission range, the total number of broadcasts can go as high as 77365 [10]. Farther nodes from the sink make more broadcasts since they receive more ADV packets coming through different paths and at different times due to propagation, communication and processing delays in wireless sensor networks.

B. Problem Statement

Gradient based routing protocols are based on the correct and efficient establishment or setup of the global gradient across the entire sensor network. The objective hence, is to establish a cost-based global gradient around the sink with the minimum node energy consumption and communication overhead and in a timely and efficient manner. The proposed mechanism should also be able to handle the changing network conditions dynamically and establish the cost-field in a time based incremental way.

C. *Details of our mechanism*

We divide the time scale into equal sized frames, each frame represented by γ. All the one hop neighbors of the sink are supposed to broadcast their minimum cost values in one γ frame. Similarly all other hop neighbors get an incremental frame for their broadcasts thus resulting in an incremental gradient setup. We make the following assumptions for our proposed mechanism.

1. The number of neighbors of each node are restricted to a predefined number 'n'. This can be achieved through topology control strategies.
2. Since we are considering the hop-count as the cost of communication for our proposed technique therefore, we assume the cost of two hop communication to be greater than single hop communication. This holds true for most practical scenarios but if it is false for some channels in the network, it would have a minimal impact on the overall performance of the proposed mechanism.
3. The clocks of all nodes are synchronized through some synchronization strategy so that all nodes follow the time frames properly.

D. *Selection of Time-frames (γ)*

The exact value of γ is calculated by the sink and this value then affects the whole cost-field setup directly. The contributing factors to the selection of γ include the number of neighbors of each node and the network conditions such as propagation delay or packet consumed cost etc. Moreover, the selection of the γ is dynamically done by the sink for each re-establishment of the cost-field gradient around the sink. The dynamic selection of γ is very important since a static time frame can not deal with the changing network characteristics and can not achieve energy efficiency in all scenarios.

The re-establishment of the cost-field after some time is also necessary for gradient based protocols in order to deal with changing network conditions. As mentioned earlier all the nodes in 'x' hop neighborhood of the sink receive one γ frame in which they are to make their broadcasts which ensures that no node in the two hop neighborhood of the sink broadcasts prior to the nodes in the one hop neighborhood. This also ensures that the cost-field is established in a time based incremental way.

For the initial establishment of the cost-field, the value of γ can be set to a smaller value since the sensor network is in most healthy operational conditions at its initialization. This initial selection of time-frame can be based on the hardware specifications of the nodes in the network, specifically the distance at which the nodes can communicate without errors and the communication delay of transferring a packet between two nodes having the specified distance between them. For the second and further refreshing of the cost-field based on the forwarding protocol used, the selection of γ is determined by the packets received at sink and the number of neighbors of each node.

The sink can statistically estimate the correct value of gamma based on the consumed cost by data packets, the packets' arrival delay, unsuccessful or dropped packets, etc. For our mechanism we chose the propagation delay as one of the deciding factor since this has been described as one of the issues in [10]. The value of γ is calculated for further refreshing of cost field by a simple equation as:

$$\gamma = (\tau * \eta) * \sigma \qquad (1)$$

where

$\boldsymbol{\tau}$ is the statistically estimated propagation delay from the packets arrived at the sink.

η is the number of neighbors of each node.

σ is a safety factor that is required to make sure the time-frames allow all nodes to make their broadcasts.

The value of σ ranges between 0.2-1.0 inclusive providing a control between two extremes i.e. flooding and total reliability. When the value of σ is 0.2, (1) results in a time frame equal to the maximum propagation delay. This value can be used when the network is in stable condition and there is a very reliable and efficient medium access control protocol used. Otherwise, a value of 0.2 for σ may result in some ADV packets collisions and multiple broadcasts. The other extreme value of σ is 1.0 which results in a large time frame and thus does not require the presence of specific medium access control protocol. In normal operation the value of σ will hardly reach any of these two extremes.

E. *Cost Field Establishment*

After selection of the γ, the sink starts the cost-field establishment by creating an ADV packet and broadcasting it to all its neighbors. This ADV packet contains only three fields:

γ_{max} : This represents the duration of time frame (γ) chosen for that particular cost-field setup. This value does not change during all the setup phase.

γ_{rand} : This represents a random number chosen by the broadcasting node between in the range of Decision Space ‘DS’. The range of decision space is between zero and the difference of γ and τ. This field is used to avoid collision of the ADV packets generated by nodes in the same hop distance from the sink since all the nodes of same hop distance from the sink are supposed to make their broadcasts in one γ frame. This value is also used by each node to set a timer for its broadcast. Such a timer is also necessary to allow more ADV packets to reach the node before it makes the broadcast.

Pc: This represents the minimum communication cost of the node that generated the ADV. For sink, this field is equal to zero.

Each node adds the channel cost between itself and the ADV generator node, to the cost in the packet. If the produced sum is less than the current minimum cost ‘MC’ of the node then the node updates its cost by setting it equal to the calculated sum. If the sum is greater than the current minimum cost of the node, the received ADV

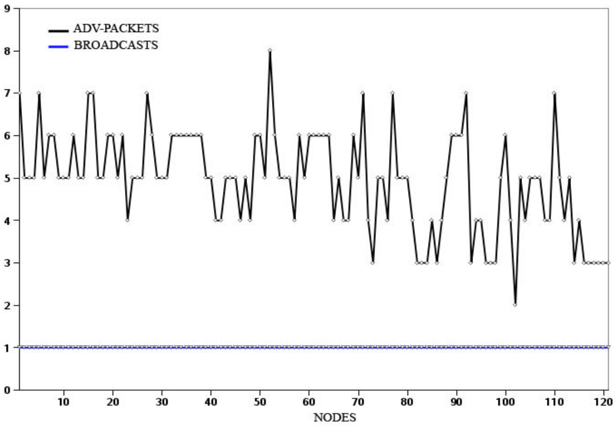

Figure 3. ADV received by nodes and broadcasts made

packet is dropped and no action is performed. This method is same as in [10]. The value of Pc increments proportionally as ADV packets go farther from sink.

Our proposed mechanism ensures that every node in two-hop neighborhood of the sink has to wait till all the one-hop neighbors of the sink have made their broadcasts. This allows every node to receive all the ADV packets from its neighbors of lesser cost before making its own broadcast.

F. Setting Timer for Broadcast

A node calculates its back-off time before making a broadcast based on the minimum cost ADV packet received and on a random value chosen by that node itself.

The main elements of a nodes broadcast time during a specified γ frame are the values of γ_{max} and γ_{rand} received in ADV packet and the nodes own random value μ, which is chosen between zero and decision space 'DS'. The back-off time is calculated through the below given equation.

$$\mathrm{BT} = \gamma_{\mathrm{max}} - (\Delta\tau + \gamma_{\mathrm{rand}}) + \mu \qquad (2)$$

where

BT is the back-off time before the node's broadcast.

γ_{max} is the duration of frame specified by the sink for the setup.

$\Delta\tau$ is the channel propagation delay i.e. current time minus ADV packet creation time. This requires that the ADV packets be time-stamped by nodes.

γ_{rand} is the μ value of the node which sent the ADV.

μ is the receiving node's own random value chosen between decision space 'DS'.

Equation (2) ensures that the single hop neighbors of the sink broadcast their minimum cost values prior to any two hop neighbors since the back-off time 'BT' values of two hop distance nodes can not be less than one hop neighbors of the sink. This also ensures an incremental establishment of the cost-field and in specified time frames.

Once the timer expires the nodes create a new ADV packet and update two fields i.e. setting γ_{rand} in the packet to the node's selected random value μ and setting Pc to the node's minimum cost MC. The value of γ_{max} is set to the same value which was received in other ADV packets.

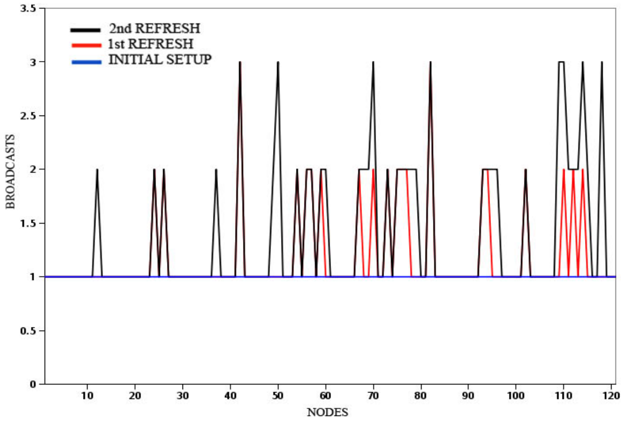

Figure 4. Impact of static time-frames on broadcasts

A node then broadcasts the ADV packet to all its neighbors. The nodes with lesser hop count readily drop the packets while the farther nodes start setting their own timers by calculating BT from the received ADV packets.

There are some issues associated with our proposed technique which were ignored up to now. First, we have taken hop count as the cost for our mechanism and thus we supposed that single hop communication cost is always less than multi-hop cost. Contrary to our supposition if there are some channels in the network where the two hop communications is less costly than one-hop communication, the order of the broadcasts may not be followed by our mechanism and some nodes may broadcast more than once.

If the propagation delays or transmission delays sum up to a larger value during the initial cost-field setup than the time-frames defined by γ, some of the nodes may broadcast more than once during first setup of the gradient, since these nodes may receive some ADV packets of lesser cost after they have made their broadcasts. This however, can be controlled by setting a relatively large value of γ for the first setup. Secondly due to the dynamic selection of time-frames for the next refresh of the cost-field, the selected γ value ensures that the communication delays can not disturb the order of the broadcasts and the global gradient is established efficiently and in time based incremental way.

V. SIMULATIONS AND RESULTS

We carried out our simulations of the proposed mechanism using OMNET++[3], a discrete event simulation framework for traditional and Ad-hoc wired and wireless networks. We carried out our simulations on different types of topologies varying in number of nodes, different in-network communication and propagation delays, different time frames and node densities. We varied the number of nodes from 100 to 1000 and dynamically changed the network conditions by simulating changing channel characteristics. We also tested our mechanism on topologies where the single hop cost was higher than two hop cost for some channels in the network. Our mechanism still yielded good results and very few nodes made more than one broadcasts. The dynamic selection of time-frames for further refreshing of cost-field from the received packets at the sink ensures that our mechanism achieves the desired results of energy

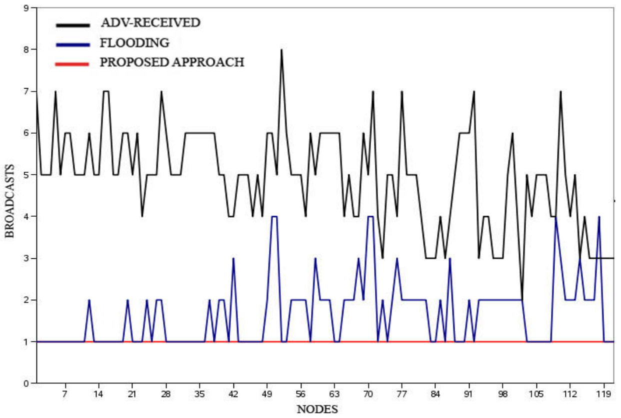

Figure 5. Our approach against flooding and received ADV

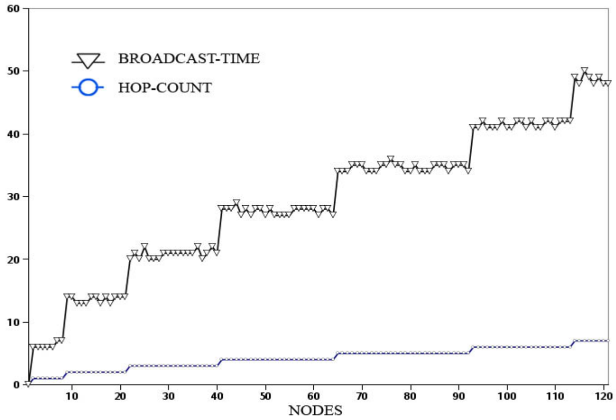

Figure 6. Time-based incremental broadcasts

efficiency and robustness even in presence of continuous network wide topological changes. The cost-field established through our mechanism achieves the same correctness that is achieved through flooding or through the technique proposed in [10].

Fig. 3 shows the number of ADV packets received by nodes and the number of broadcasts made. As in Fig. 3 our mechanism ensures that nodes broadcast only once even when they receive number of ADV packets. This is so because the back-off time of each node is directly proportional to the time frame selected by sink, in-network propagation delay and some random safety factor chosen by nodes independently.

Fig. 4 shows the impact of static approach for cost field establishment. As we have been mentioning, if the value of γ is not changed dynamically, the cost-field can not be established energy efficiently for every required cost-field reestablishment. The value of γ was set to 3ms for the initial cost-field setup and it achieved the desired results of one broadcast per node results in specific time-frames but as can be seen in Fig. 4, the same value of γ does not achieve the same results for 1st and 2nd refresh of the cost-field since the network conditions have now changed and the nodes make proportionately higher number of broadcasts as the network states change.

Fig. 5 shows a comparison of our technique and flooding. Although both establish the same cost-field and also receive the same number of ADV packets, our approach is more energy efficient as it makes only one broadcast per node and also achieves desired results in specific time-frames

Our proposed approach establishes the cost-based global gradient in time based incremental way. This has been shown in Fig. 6. The blue line represents the minimum cost 'MC' values which are equivalent to the nodes' minimum hop-count and the black line represents the different time frames where the nodes make their broadcasts.

VI. CONCLUSION & FUTURE WORK

In this paper we proposed a new mechanism for cost-based global gradient setup for gradient based routing protocols in wireless sensor networks. Our proposed mechanism is robust to changing network conditions as it adapts itself to the new conditions through statistical analysis of the packets received at the sink. Our proposed technique also achieves the desired results in energy efficient and timely manner.

Wireless sensor networks are dynamic in many aspects. We considered the dynamics of communication in terms of delay and error rates in this paper. Other aspects such as node mobility and the addition of new nodes etc still need to be investigated. The proposed technique has been simulated with generic specifications of nodes and routing protocols. In future the technique can be tested for the mobile and hostile environment scenario with defined node capabilities and specifications.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y.Sankarasubramanium and E. Cayirci, "A Survey on Sensor Networks," IEEE Commun. Mag. August 2002, pp. 102-114.

[2] C. Intanagonwiwat, R. Govindan and D. Estrin, "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks," ACM MOBICOM'00, 2000.

[3] OMNET++. A Discrete Event Simulation System. http://www.omnetpp.org

[4] R. D. Poor "Gradient Routing in Ad-hoc Networks," http://www.media.mit.edu/pia/Research/ESP/texts/poorieeepaper.pdf

[5] G. Potie, W. Kaiser, "Wireless integrated network sensors," ACM Commun. May 2000 vol. 43, pp. 51-58.

[6] F. Schewetzer and B. Tilch, "Self Assembling of Network in an Agent Based Model," J. Phy. Review E, 2002 Vol. 66, Article 026113.

[7] R. C. Shah and J. M. Rabaey. "Energy Aware Routing for Low Energy Ad hoc Sensor Networks", in Proc. IEEE Wireless Communication & Networking Conference, 2002.

[8] R. Szewczyk, E.Osterwil, J. Polastre and M. Hamilton, "A Mainwaring Habitat Monitoring With Sensor Networks," Communications of the ACM June 2004 Vol. 47, No 6, pp 34-40.

[9] J. Wu, P. Havinga, "Reliable Cost-based Data-centric Routing Protocol for Wireless Sensor Networks," in Proc. Seventh ASIC International Conference on Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing. SNPD'06, IEEE, 2006.

[10] F. Ye, A. Chen, S. Lu and L. Zhang "A Scalable Solution to Minimum Cost Forwarding in Large Scale Sensor Networks," in Proc. Tenth International Conference on Computer Communication and Networks, 2001.

[11] F. Ye, G. Zhong, S. Lu and L. Zhang " Gradient Broadcast: A Robust Data Delivery Protocol for Large Scale Sensor Networks", Springer Science, Wireless Networks 11, pp. 285-298, 2005