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MAXIMIZING LIFETIME OF –POWERLIMITED NETWORK WITH ACTIVE MINIMUM SPANNING TREE AGGREGATION

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ABSTRACT

Recently proposed "Harness" is a system level group communicationware that enables a large number of nodes to exchange programmable network information using various communication patterns. It offers both scalability and versatility in message communication between a large set of nodes connected via any network. In this paper we show how the scalable message aggregation offered by the Harness can be used to set up a group communication pathway for power limited ad hoc wireless network. While, the harness can compute various patterns of communication in a distributed fashion and guide data as per the pattern, we show that *minimum spanning tree* with active message aggregation is one of the most power efficient modes. In this paper we show how dramatically it can improve the network life time.

KEY WORDS

Power aware, Ad hoc wireless, sensor computing

1.Introduction

In this paper we propose a novel mechanism to maximize lifetime of an adhoc wireless network by ensuring minimum energy transmission (MET) with active data aggregation. Even though, Heinzelman [1] et al and Jae-Hwan et al [2] argue that minimum energy routing is not a feasible solution since its network partitioning time [3] decrease due to overuse of some nodes which fall on the minimum energy transmission (MET) route, however, we show, in this paper that this does not always hold, specifically whenever after aggregating data the size of the data does not increase significantly. More over, if data aggregation is not feasible, harness can deploy other schemes for maximize lifetime without much effort.

An ad hoc network has limited power resources being operated by stand-alone battery. Moreover, there can be other constraints associated with QoS provisions like delay and bandwidth. Hence, maximizing the lifetime of a node and the network as a whole is a challenging issue since nodes might be responsible for not only in merely transmitting its own collected data but also in forwarding others data. Chen et al [4] mentioned characteristics a good power saving technique which includes insuring delay and bandwidth equivalent to that provided by a backbone ad hoc network formed by all the nodes in the network. A sensor network requires scalable messaging among large number of nodes often connected in an ad-hoc power constraint network. Hence, the underlying technique should be such that the overhead, due to coordination among nodes, is as low as possible. Otherwise, nodes will use up its scarce power resource more in coordination rather than in collecting and forwarding data. Moreover, the overlying protocol should not be burdened by any energy saving mechanism [5].

When in power safe mode a node can be either in wakeup or in sleep state. The wake up can again be subdivided into transmitting, receiving, listening, forwarding and any combination of these. Recent research shows that foremost power usage occurs due to being awake rather than listening or receiving [5]. So in any scheme it is important to minimize the time of wakeup stage in order to maximize the lifetime of the ad hoc network. Moreover, Heinzelman et al have argued that power expended to transmit data exponentially varies with distance [1,6]. Hence, whenever possible routing a packet to the destination node, which can be a gateway node or a base station, via intermediate nodes (i.e. using multi-hop rather than direct transmission to destination) saves energy. In addition, Kulik et al [7] argue that computation in a node is cheaper than transmitting and receiving data. Therefore, node level data aggregation in harness can save energy to a great extend. At the same time, aggregated data gives more useful information.

In this paper we are presenting a novel approach of harness that can be used to maximize sleep phase of nodes preserving maximum delay and bandwidth using minimum spanning tree. Harness uses cost functions shown to be effective in maximizing lifetime of an ad hoc network. Further, it can reduce amount of data to be transmitted all over the network.

In remaining paper, we discussion related works in section 2 followed by harness concept in section 3. Then section 4 illustrates the operation of the harness in power-limited network. Finally, before concluding, in section 5

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we share empirical results depicting the performance of the proposed harness system.

2.Related Work

Some routing algorithms [8,9,10] in mobile wireless networks uses shortest-path routing where the number of hops is the path length. However, [11,12,13,14,15] argue that the optimum routing in wireless and mobile networking with minimum energy constraint, is a variation of spanning tree problem rather than shortest path.

Chang and Tassiullas [2] uses solutions for maximum flow (for a single power level) and linear programming (for multiple power levels) to distribute wireless traffic among various paths so that batteries of the nodes drain-out in a uniform way in order to maximize lifetime of a network. Chalermek et al [5] uses greedy incremental tree (GIT) for data aggregation and energy saving. In SPAN [4], coordinators are elected periodically by rotation, which are awake while other non-coordinator nodes remain in power saving mode. Chalermek et al [16] refers the problem of aggregating data with minimum cost as set-cover problem. SPIN [7] uses meta-data to find similarity between data in order to aggregate sensor data. Our approach is similar to SPIN in the way data each node needs to know about its singe hop neighbors. However, in SPIN the there is no provision to put a node into sleep state when it is not taking part in data collection or data forwarding.

Several researches in sensor networking area are recently investigating means for scalable data aggregation [17]. In [18] aggregation is done based on Center at Nearest Source (CNS), Shortest Path Tree, or Greedy Incremental Tree (GIT). PEGASIS [19] creates a chain path between network of sensors to gather and fuse data as data passes over the chain. Then fused data is sent to base station by one of the randomly chosen sensors located in the chain. LEACH [1] is a cluster-based protocol using data fusion. Younis et al [20] used multiple clusters headed by non-energy-constraint gateway nodes for increasing lifetime of a sensor network. Gateway nodes set the route along with transmission time for other nodes in the cluster.

Feeny [2] proposes an asynchronous power save protocol based on sleep/wakeup cycle. [5] observes that the foremost energy expenditure of a node is due to being awake. Hence, whether a node is sending or receiving is not the dominant factor. Therefore, to maximize lifetime of a node it should spend in sleep state as much as possible. Feeny [5] uses the facts that if all nodes are awaken half of the time then there are overlapping awake-periods irrespective of phase difference between any two nodes. However, this principle of nodes being awake half of the cycle causes the limitation that even if the interval needed to send data from one node to other node does not require half of the cycle still nodes will be awake more then half of the cycle causing wastage of scarce power resource.

3.Harness Approach

We are exploring an experimental dynamic mechanism for state information polling and propagation inside network with similar embedded information synthesizers, which seems to be both scalable and versatile[21,22]. In this paper, we explain the application of the harness in ad hoc network to maximize its lifetime of ad hoc network by using the minimal spanning tree. There is an added cost of computation. However, the power cost of computation is order of magnitude less than the power cost of communication [5]. Thus, as we will show the sensor computation significantly reduces the power waste.

3.1. Harness Architecture

The harness is in charge for initiating, propagating and responding to a series of well-coordinated messages between the nodes in a network. The harness once installed in network nodes, can act in three roles-- *session initiator*, state *synthesizer*, and *terminals*. The initiator acts as the communication agent in the network layer for the application that actually requires the information. The synthesizer propagates the state requests and processes the returning states from the terminals. The harness controls the communication pattern and thus deals with the efficiency of messaging. Harness system accepts a set of plug-ins, which determines the content of these messages, and how they are propagated and aggregated at the junction points.

3.2. Messaging

The harness system is designed to operate with a novel request-reply-update messaging scheme. It has three types of messages *request*, *reply* and *update*. The *session initiator* decides how often a request is generated. The request messages are sent to the *terminals* if they are immediately connected, or to synthesizers for further downstream propagation. A synthesizer upon receiving a request, propagates the query by generating a new request message to the down-stream nodes. However, at the same time it might also generate an immediate reply for the requestor. The replies from synthesizers may contain current local state and/or past remote states. The reply might also be used to acknowledge receipt of a request indicating that the receiver will generate request further down-stream. The terminal nodes send replies to their respective requestors. The terminal reply contains locally retrieved current states. The terminals or *update initiators* initiates return trip of information by generating update messages. In the return trip of information, the synthesizer nodes aggregate the information and at each stage generate update messages for their requestors. Once a node receives all or specific number of update messages

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from its immediate down-stream nodes or on timeout, it updates the network local state variables and generates a new update message. The update message contains a synthesized summary of information calculated from all its immediate downstream nodes. In essence, the request-reply phase allows collection of local immediate states.

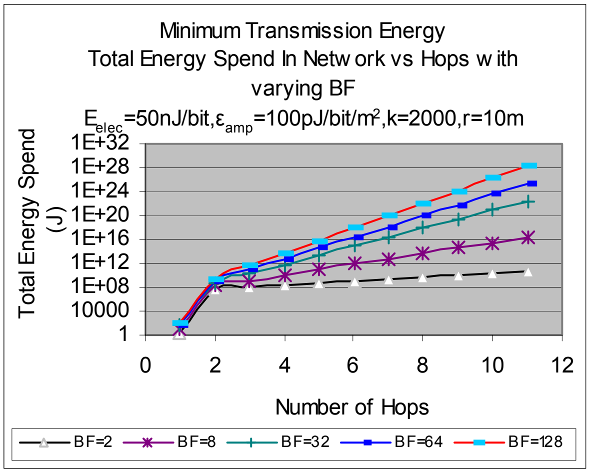

Figure 1: Total Energy Spend for MTE

The reply mechanism allows immediate probing into current local states and past synthesized remote states, while the update message retrieves aggregated latest remote states.

3.3. State Composition

Harness system accepts a set of six-plug-ins which are called *request generator*, *reply generator, update generator, request aggregator*, *reply aggregator,* and *update aggregator.* These modules together determine the content of these messages, and how they are aggregated at the junction points. They work via a virtual *slate*. A copy of which is maintained in each of the nodes. The *request generator* specifies the request message describing the fields it wants from the slate of its down-stream node. *Reply aggregator* (or *update aggregators*) in a similar fashion is invoked each time a reply (or update) is received by the harness. They perform domain specific processing of the reply message fields and similarly update their own slate variables. The update generator sends the slate variables synthesized by the update aggregators to the upstream node.

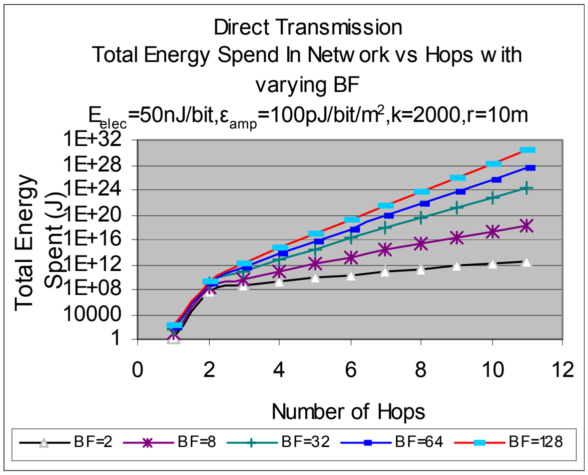

Figure 2: Total Energy Spend for DT

At the heart of the composition ability is the transfer functions of the intermediate synthesizers. The request and update phase can be represented by equations:

$$S_t^j = \Phi(\vec{\mathrm{E}}(Q_t^{i,j,-}), M_t^j, S_{t-1}^j)\ and\ Q_t^{-,j,k} = \vec{F}(S_t^t) \quad 1$$

$$S_t^j = \Psi(\overleftarrow{F}(P_t^{-,j,k}), M_t^j, S_{t-1}^j),\ and\ P_t^{i,j,-} = \overleftarrow{E}(S_t^t) \quad 2$$

Here S_t^j is the local *slate state* at event time t at node j, $\vec{E}$ is the *request receiving* filter (RRF), M is the *local network state* (such as MIB variable), $\vec{F}$ is the *request forwarding* filter (RFF). $Q_t^{i,j,-}$ is the arrived request from parent i, to node j and $Q_t^{-,j,k}$ is the propagated requests to children k. $\overleftarrow{E}$ is the *update forwarding* filter (UFF), $\overleftarrow{F}$ is the *update receiving* filter (URF). $P_t^{-,j,k}$ is the arrived update from child k, and $P_t^{i,j,-}$ is the propagated update to parent i. While the filters determined the information propagation rules, composition functions $\Phi()$ and $\Psi()$ together determine the message content.

4.Harness for Maximizing Lifetime of Ad Hoc Network

There is a general trend to use either shortest path or variations of spanning tree in adhoc sensor network. The cost function differs depending on the criteria that are stressed in a specific application. In this paper we are assuming that the nodes are static during each phase of harness execution. A command node [23] uses the data collected by the ad hoc network. The cost function defined in [20] is used. The programmability of the harness for MST is defind in [22].

Heinzelman *et al* showed that even directed transmission (DT) outperforms MET [1]. Here, we show if data aggregation is possible at intermediate nodes then MTE can maximize lifetime of ad hoc network. Given E_{elec}=50nJ/bit, ε_{amp}=100 pJ/bit/m^2, number of bits k=2000,

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distance between each node r=10m, and for simplicity assuming a balanced tree with branching factor, b, and depth, d, energy spend in MTE:

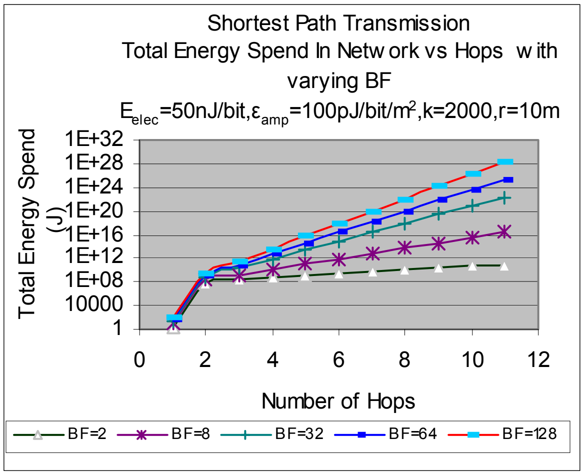

Figure 3: Total Energy Spend for SPT

$E_{MTE} = (b^{d+1}-1)/(b-1)*(E_{elec}*k + \varepsilon_{amp}* k*r^2)+(b^{d+1}-1)/(b-1)*(E_{elec}*k)$. Figures 1, 2, and 3 approximate the total energy dissipated for SPT, MET, and DT. MET has lowest dissipated energy. Table -1 shows for different probing depths the amount of dissipated for branching-factor of 128.

Table 1: E_{MTE}, E_{SPT}, and E_{DT} For BF=128

Depth	MTE	SPT	DT
2	3.32E+11	3.35E+11	1.31E+12
4	5.44E+15	5.48E+15	8.63E+16
6	8.91E+19	8.98E+19	3.18E+21
8	1.46E+24	1.47E+24	9.28E+25
10	2.39E+28	2.41E+28	2.38E+30

The cost of sending data packet via a path is the accumulated cost of all the links traversed. Younis *et al* [20] proposed seven cost factors associated with a link while that is used in transmitting a packet optimizing delay which restricts overuse of any specific node to increase time of network partitioning. The cost factors taken into considerations are: communication cost (CF_0), energy stock (CF_1), energy consumption rate (CF_2), relay enabling cost (CF_3), sensing cost (CF_4), maximum connection per relay (CF_5), propagation delay (CF_6) and queuing cost (CF_7). Total cost incurred traversing a link between *i* and *j* is:

$$c_0*(distance_{ij})^l+c_1*f(energy_j)+c_2/T_j+c_3+c_4+c_5+c_6*(distance_{ij})+c_7*load.$$

Here, c_0 is the weighting constant and l depends on environment. Function f favors battery with higher remaining power. c_2 is another weighting constant T_j is the expected time for node *j* to reach minimum acceptable energy threshold. c_3 is the relaying cost. c_4 is the constant added if the node is sensing. c_5 controls numbers of nodes associated with a node by adding extra cost when a node reaches pre-assigned number. c_6 favors closer node while the factor c_7***load*** helps to avoid dropping or delaying data packets.

Whenever data aggregation is possible, MET (minimal energy transmission) gives total network wide energy expended to be minimal in each round of data collection. Heinzelman et al and others argue [1,20] that minimum energy routing is not a feasible solution since its network partitioning time [3] decreases due to over use of some nodes which fall on the minimum energy transmission (MET) route. However, if data can be aggregated [17] then data is not forwarded for every data packet received; rather only once in one update phase a node forwards an aggregated data packet. Moreover, the power dissipated from a node depends on how long a node is in wakeup state. Using the cost function mentioned, we can impose an upper bound on number of nodes associated with a node. Thus, overuse of any specific node does not occur even if a node falls in MTE route. Hence, the nodes dissipate energy at a uniform rate improving network-partitioning time.

5.Simulation Results

We have performed statistical simulation to project the performance of the harness system under various constraints. The performance depends on the characteristics of the programmable components (complexity of the plug-ins, message size etc.) as well as on the network (such as bandwidth, probing depth, number of nodes etc.) and platform characteristics (link latency, messaging delay, etc)

5.1. Link Latency

Link latency is generally one of the most distinguishing aspects of a network environment for application involving small data. The first simulation result, presented in Figure 4, shows the effect of link latency on the update delay for sessions with various probing depths (d=4-7). In this simulation we assume that message size of first request message is 100 bytes. Here the request generation, update generation and aggregation is 2 ms each, the request aggregation, reply generation and aggregation is 0.5 ms each, and the bandwidth is 56 kbps. We assume the probability of timeout is .0005 and average branching factor is 3 and timeout factor is 2τ where τ is the link latency. Update delay, in seconds, is drawn in the vertical axis while link latency, in seconds, is on the horizontal axis. As the graph shows, when the probing depth is relatively low, less than 5 ms, update delay remains below 1 sec. A large network-- as large as of depth 7, can be probed with this system within this time bound if the link latency is small. The graph also shows that a network with larger latency can still avoid the timeout and maintain performance scalability if the depth is small. As the link delay becomes larger, the effect of intermediate timeouts at deeper probes becomes prominent. As can be observed, in the extreme end, a depth 7 network showing about 300 ms delay can still be probed in about 10 second with the system.

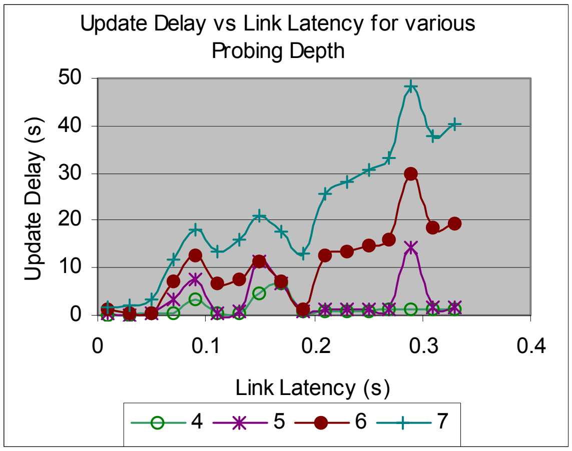

Figure 4: Update Delay

5.2. Scalability

The next experiment depicts scalability of the harness. For this experiment we studied the average time to probe very large networks. We assumed a network of depth 7 and let the branching factor at each node vary from 2-9. Figure 5 plots the update time experienced by network of various sizes. For comparison we also show the number of nodes that can be probed for each case (the right y axis and the bars show the number of nodes for each BF). We repeated the simulation for various link latencies. As can be seen about a million nodes can be probed in about 20 seconds. With 10 fold increase in the number of nodes probed the increase of update delay is only 1 second. Such scalability and the associated programmability of the probing task can make this technology a potential tool for accelerating in collecting data in sensor networks.

6.Conclusions

The key to the system's **scalability** and **versatility** are the embedded aggregators. Since local state dependent aggregation is performed inside a network, it reduces communication and thus enhances the system's scalability. Aggregators also provide the ability to compute network relative deep composite statistics, enhancing the versatility of its ability to collect network states. Harness offers both scalability and versatility in message communication between a large set of nodes connected via any network. In this paper we show how the scalable message aggregation offered by the Harness can be used to set up a group communication pathway for power limited ad hoc wireless network. While, the harness can distributedly compute various patterns of communication and guide data as per the pattern, the results show that minimum spanning tree with active message aggregation is one of the most power efficient modes. In this paper we show how dramatically it can improve the network life time.

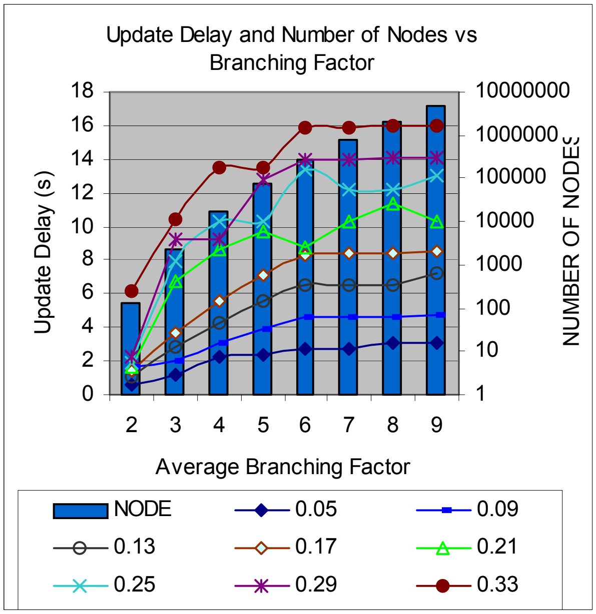

Figure 5: Update Delay and Number of Nodes

The scope of this paper does not permit discussion on implementation. It is non-trivial nevertheless can be realized at user space as *deamons*. Embedded implementation can cut down some overhead and will be critical for sub-second range probing cycles. Implementation on some form of active platform can further facilitate matters such as remote deployment, and seamless secured execution of the plug-ins. The harness plug-ins require very limited form of programmability compared to general active net proposal. The proposed harness is perhaps one of those cases where provisioning even very low-grade programmability can be highly rewarding. The harness increases state visibility of network. In effect it facilitates high pay off smart optimizations for numerous applications, which are not possible today due to the black box nature of current network. Interestingly, such a network layer utility is not only crucial for building a new generation of network aware applications but it is also vital for many of the current problems of different types of networks, interestingly, many of which are arguably artifacts of the opacity of current network design. Currently, we are exploring its active network based simulation. The work is being supported by the DARPA active network Research Grant F30602-99-1-0515.

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