Energy-efficient routing in wireless sensor networks for delay sensitive applications

D. Ranganathan, P. K. Pothuri, V. Sarangan, and S. Radhakrishnan

I. INTRODUCTION

Recent developments in wireless technologies and embedded computing systems have led to the emergence of un-attended wireless sensor networks (WSNs). Regardless of the limited energy availability in the sensor nodes, WSNs have enabled a plethora of new services and applications. Certain applications, such as volcanic monitoring – where sensor nodes are deployed to monitor the seismic activities and emission levels of volcanic craters, are highly delay sensitive and data should be transmitted to the control center within a prescribed delay in observance of any unusual activity. The sensor nodes must also exercise care so as to not spend excessive amounts of energy in meeting the prescribed bound on the data transfer delay. Such applications give rise to the delay-constrained, energy-efficient routing problem (DCEERP), where in, given a delay bound of d' seconds, the task is to find a path from a sensor node to the sink with the lowest energy consumption, such that the total transfer delay incurred along the path is less than d' seconds. Current solutions that target this DCEERP are inadequate as they do not model the channel access delays caused by the MAC layer. In this work, we propose a new routing strategy that employs power control and also models the channel access delay caused by 802.11 like MAC layers to solve the DCEERP.

II. PROBLEM DEFINITION AND ASSUMPTIONS

Let s be a sensor node generating time sensitive data to be sent to the sink τ; d' be the maximum end-to-end delay that can be tolerated in the data transmission; Let P denote the set of paths available between s and τ; d_i and E_i denote the end-to-end delay and energy consumed along the path $P_i \in P$. Given the above, the DCEERP can be stated as follows:

DCEERP: Find a path P_{i^*}, such that $P_{i^*} \in P^c$, and $E_{i^*} \leq E_j, \forall P_j \in P^c$ where, $P^c = \{P_i | P_i \in P \text{ and } d_i \leq d'\}$.

This problem belongs to the class of constrained-path optimization problems and is NP-Complete [2]. Therefore, only heuristic solutions for this problem are possible. The authors proposed a heuristic for the above problem in their earlier work [3]. However, this solution is applicable only under certain assumptions that restrict the communication pattern among the sensor nodes. The proposed work aims to solve the DCEERP for more generalized communication patterns thereby allowing better utilization of network resources. We propose a network architecture and routing framework that enables us to model the MAC layer access delays, which in turn, allows us to better estimate the end-to-end delays across various paths in the network.

Assumptions:

1) The sensor nodes are assumed to be are stationary in the network and are aware of their geographical location.
2) The nodes are equipped with two radios: a low power radio for short-range communication and a high power radio for long-range communication. Both radios operate at different frequencies and hence there is no interference in simultaneous transmissions. Since short-range radio consumes lesser power than long-range radio, it is made the default radio for the sensor nodes. Long-range radio is employed only when the delay bound cannot be met using the short-range radios and it's transmission power (hence the range) is adjustable.
3) The sensor nodes use 802.11 like channel access scheme for each of the two wireless channels.

III. PROPOSED NETWORK ARCHITECTURE

The geographical area over which sensors are deployed is divided into *sectors* of angular width θ and *annular bands* of thickness b as shown in Figure 1. The sensed region is viewed as a grid in polar co-ordinates, with the sink τ being at the center. The network grid is generated when the sink advertises the values of θ and b over the entire network. As each sensor node is location aware, it can determine the grid cell to which it belongs to after the sink's advertisement. Each cell has a `gateway`– which is nothing but a node close to the cell's center that aggregates the information sensed in that particular cell and forms a communication backbone with other gateways. After hearing the sink's advertised values of θ and b, sensor nodes located within a small distance ϵ from a cell's geographical center start a random timer. The node whose timer expires first advertises itself as the cell's gateway. Other nodes on hearing the advertisement, cancel their timers.

There exist two phases – *intra-cell* and *inter-cell* phases, in relaying data from a sensor node to the sink. In the *intra-cell* phase, a sensor node transmits data directly to the gateway located in the same cell using its short-range radio. As the distance is limited, a direct transmission is possible and we assume that the delay involved within the intra-cell communication is d'' seconds, with $d'' < d'$ seconds. In the *inter-cell* phase, the gateway relays the data to the sink τ within the remaining $d' - d''$ seconds along a suitable path. The gateways use short-range radios to communicate directly with neighboring gateways and

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long-range radios to communicate with non-adjacent gateways. Our solution aims at developing a heuristic for finding an energy-efficient path for the inter-cell phase of the data transfer. The communication pattern in the network is streamlined by allowing a gateway to act as an intermediate hop only for the sensory data that originates in the same sector as the gateway.

IV. SOLUTION DETAILS

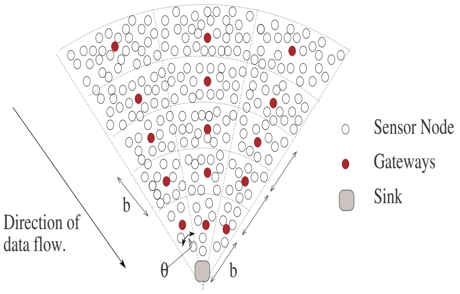

Fig. 1. Network Architecture.

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1) If the delay along $g_N$'s basis path is less than $d$,
    a) The basis path from any given gateway is its DCEERP solution.
    b) Return.
2) Else
    a) For each $n = 1$ to $N$,
        i) Since the delay across short-range links can be calculated, remove all
           paths from $\mathcal{P}_n$ that may not satisfy the delay constraint.
        ii) Arrange members of $\mathcal{P}_n$ in the increasing order of energy consumption.
    b) $U \rightarrow \oslash$
    c) Iterate the following until the delay for the solution path from each of the
       gateway does not change anymore.
        i) For $n = N$ to 2,
            A) Use the current value for $U$ to determine the lowest index path
               $P_n^* \in \mathcal{P}_n$ that satisfies the delay constraint.
            B) Modify $U$ to add any new gateway in $P_n^*$ that may use its long
               range radio. Add the appropriate range as well.
    d) Return.
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Fig. 2. Procedure to determine DCEERP solution paths.

Let $g_{m,n}$ denote a gateway node located in sector m and band n. Let the bands be numbered in the increasing order of their distances from the sink, with the sink being at band 0. Lets consider a specific gateway, say $g_{3,3}$ – the gateway in the third sector and third band. As per the communication pattern described before, the possible intermediate hops for $g_{3,3}$'s data are $g_{3,2}$ and $g_{3,1}$. With these intermediate hops, the possible paths are $\{g_{3,3}, g_{3,2}, g_{3,1}, \tau\}$, $\{g_{3,3}, g_{3,1}, \tau\}$, $\{g_{3,3}, g_{3,2}, \tau\}$, and $\{g_{3,3}, \tau\}$. Since the various path options are along the same sector as the source gateway, unless required, we shall refer to a gateway $g_{m,n}$ as g_n. In general $N_P(n)$, the number of paths available for a gateway g_n is given by $N_P(n) = \sum_{i=1}^{n-1} N_P(i) + 1$ and can be shown to be $O(n^2)$. The idea behind our heuristic solution to DCEERP is as follows. Given a gateway g_n, we first enumerate $\mathcal{P}_n$, the set of various paths that are available from g_n to the sink. We then arrange the paths in the increasing order of their energy consumption. We then estimate the delay for each of the paths and pick the path with the lowest index that satisfies the delay constraint as the DCEERP solution.

Energy Estimation: The energy required to transmit data in wireless medium over a distance r is given by Kr^{α}, where K is a proportionality constant and α is the attenuation exponent with $\alpha \geq 2$. Energy E spent along a given path P can be determined by summing the energy expended in the individual links along the path. Since the location of the sensor nodes do not vary with time, given b, θ and the gateways along a path particular path P_i, the energy expended along that path can be calculated.

Delay Estimation: Given two gateways g_u and g_v with $v < u$, the access delay $\mu_{u,v}$ across the link (g_u, g_v) can be estimated if the set of gateways that can interfere with either g_u or g_v's transmissions can be identified [1]. Since the short-range radio is the default and its range is constant, the set of gateways that can potentially interfere with a short-range link can be easily identified and the the channel access delay along such links can be calculated using the procedure outlined in [1]. Estimating the interference set of long-range links is not straightforward. Figure 2 outlines a high-level description of the procedure that simultaneously estimates the interference set of long-range links and solves the DCEERP. The following notations will be useful in understanding the procedure. Let N be the band within the query region that is farthest from the sink along any sector and $d = d' - d''$ be the inter-cell delay constraint. Let the *basis path* from a gateway be composed only of the short-range radio links. For any gateway g_n, the basis path is given by $\{g_n, g_{n-1}, g_{n-2}, \cdots, g_2, g_1, \tau\}$. Let U be the set that includes the gateways that use their long-range radios along with the appropriate range.

V. CONCLUSION AND FUTURE WORK

We have proposed a heuristic approach for finding energy-efficient paths that satisfy the delay constraints in sensor networks. Currently, we are performing simulations to check the convergence of the DCEERP solution. Our future work is to: (1) incorporate the residual energy of the nodes in DCEERP solution so as to increase the network lifetime; (2) study the network scalability issue of increased cell area by considering the intra-cell phase delays in calculating the delay constrained paths.

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