

ENERGY-EFFICIENT ROUTING IN WIRELESS SENSOR
NETWORKS FOR DELAY SENSITIVE APPLICATIONS

By

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CHAPTER 1

INTRODUCTION

Fast growing wireless technologies along with low cost embedded computation devices and contemporary design of communication infrastructure have resulted in rapid development of Mobile Ad hoc Networks. Such networks are self-organizing and their nodes communicate directly to each other using wireless transceivers along multi hop paths without the need of a fixed infrastructure(as opposed to cellular networks). This distinguishing feature has shifted the focus of wireless community towards ad hoc networks and they are considered as the technological counterpart of the concept of ubiquitous computing.

1.1 Wireless Sensor Networks

Wireless Sensor Networks(WSNs for short) are a certain type of un-attended ad hoc network consisting of numerous small independent sensor nodes that are either deployed in the activity region or nearer to it. The sensor nodes in the network are self-contained units containing advanced sensing functionalities, limited battery(energy), radio, and a minimal amount of on-board computing power. These sensor nodes exchange information in order to build a global view of the sensed region and the information is made accessible to the external user through one or more gateway node(s) [1]. Such networks are increasingly attractive means to enable a variety of applications and services. Some of the application domains include environment monitoring, health, military and home [2]. However these applications are delimited to a great extent due to the limited energy at the sensor nodes as it directly corresponds

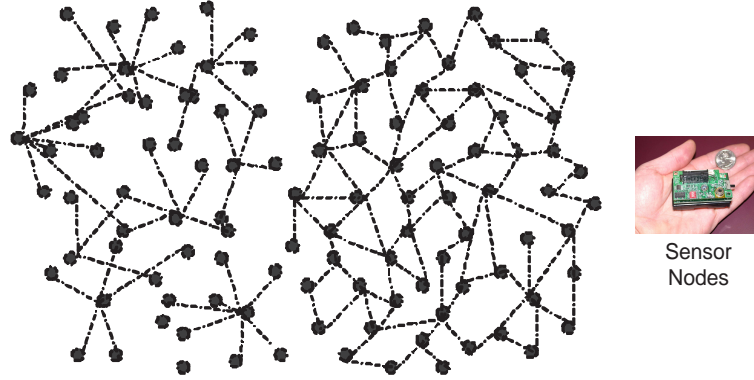


Figure 1.1: Sensor Networks field

to network operational lifetime. In this context, since most of the energy is expended in transmitting the information between the sensor nodes rather than sensing, many academic and industrial efforts [3, 4, 5] focused on proposing energy-efficient routing protocols that involves several short-range multi-hop communication in lieu of direct long-range communication in relaying data between the sensor nodes. This routing strategy curtails the amount of energy spent by the sensor nodes but tends to increase the end-to-end delay involved in transfer of sensory data from the field to the sink.

1.2 Delay-Constrained, Energy-Efficient Routing Problem

Certain applications such as *Volcanic Monitoring* are highly delay sensitive, where sensor nodes are deployed to monitor the seismic activities and emission levels of volcanic craters and data should be transmitted to the control center within a prescribed delay in observance of any unusual activity [6]. Using power control or topology control, such sensitive delay requirements can be possibly met. In topology control, the nodes transmit the sensory data using long-range radio links to distant nodes. The transfer delay incurred in such transmission is lowered as the data is relayed in fewer hops to the sink node but with higher energy consumption. A trade-off exists between the energy consumed in the data transfer and the incurred data transfer delay, thus giving rise to Delay-Constrained, Energy-Efficient Routing Problem (DCEERP) in

many WSNs applications. In DCEERP, 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. Since the wireless medium is broadcast in nature, significant delay is caused by the MAC layer in accessing the channel to transmit data, especially in multi-hop communication. Current solutions that target this problem are inadequate as they do not model the channel access delays caused by the MAC layer and hence the quality of any DCEERP solution that does not model the MAC delay is emphatically poor. Few of such existing protocols are discussed in the related work section.

1.3 Thesis Overview and Organization

This thesis work presents a methodology to solve the aforesaid DCEERP by introducing a network architecture and a routing strategy that employs topology control to enable modeling of the channel access delays caused by 802.11 like access schemes. This in turn, allows us to better estimate the end-to-end delays across various paths between the source and the sink nodes. Firstly, we enumerate the set of paths available between the source and the sink node and index them in increasing order of energy consumption. We then estimate the end-to-end delay incurred in each of the paths in the indexed set and then select the lowest index path that satisfies the delay constraint.

This thesis work is organized as under: In chapter 1, a brief introduction to the thesis work is presented. In chapter 2, few highlights is provided on the existing solutions in comparison to our work. Chapter 3 details on problem formulation and necessary assumptions being made in solving the DCEERP problem. This chapter also presents a detailed design of the proposed architecture and the data transmission phases. Chapter 4 elaborates on the DCEERP solution details in estimating delay and energy along the paths and the algorithm used. Numerical results are presented

in chapter 5. Finally, the conclusion is made in 6.

CHAPTER 2

RELATED WORK

The growing interest in sensor networks and continual emergence of new applications inspired various efforts in attempting to address the problem of energy-efficient, delay-constrained routing in sensor networks. The sensor nodes are heavily constrained in terms of energy consumption, delay guarantee, processing capacity and storage and hence require careful resource management. This chapter highlights about the existing protocols and provides a distinction between the proposed work from other work.

Hea et al. [7] proposed a routing protocol called SPEED that supports real-time communication in a sensor network and also provides soft real-time end-to-end delay guarantees. Each node in the network maintains information about its neighbor nodes and uses Stateless Non-deterministic Geographic Forwarding(SNFG) in routing packets without requiring the end-to-end path setup. SPEED maintains a desired delivery speed for every admitted packet in the network. The term *delivery speed* is defined as the rate at which the packet travels in a straight line from the source to destination. This definition of speed makes the end-to-end delay in the network proportional to the distance between the source and the destination. The routing algorithm estimates the end-to-end delay for the packets by considering the distance to the sink and the speed of the packet before making the admission decision. Moreover, SPEED can provide congestion avoidance when the network is overloaded. The routing module in SPEED called Stateless Geographic Non-Deterministic forwarding (SNFG) along with other modules works at the network layer, as shown in figure 2.1 [7]. The beacon exchange mechanism gathers information about the nodes

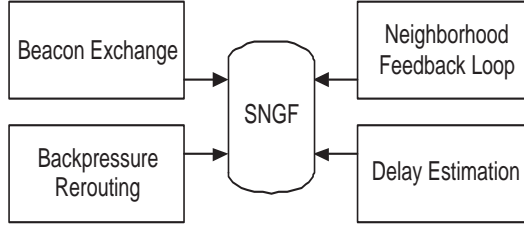


Figure 2.1: Routing Components of SPEED

and the associated location. Delay estimation module calculated the elapsed time when an ACK is received from a neighbor as a response to a transmitted packet. The SNGF module selects the node that meets the speed requirements based on the delay values provided by the delay estimation module. If none of the nodes satisfy the speed requirements, the relay ratio of the node is checked. The Neighborhood Feedback Loop module calculates the the relay ratio by examining the miss ratios of the neighbors of a node and feeds it to the SNGF module. If the relay ratio is less than a randomly generated number between 0 and 1, the packet is dropped. The back-pressure re-routing is responsible to overcome packet delivery degradation due to congestion. SPEED takes into account the delay in the transmission caused by channel access mechanisms. However, it does not attempt on energy efficiency along the selected path. Also the idea of per-flow reservation leads to scalability issue due to the highly dynamic link and route characteristics of WSNs.

Lu et al. [8] proposed RAP, a real-time communication architecture for large-scale wireless sensor networks. It provides a set of high-level query and event services for applications. RAP proposes velocity-monotonic scheduling(VMS) as its default packet-forwarding scheme on the wireless medium. Similar to SPEED, in order to meet the end-to-end latency bound, a packet must maintain some desired average speed or velocity across the network towards the target. This velocity is determined by the timed delay bound and the distance between source and target nodes. RAP prioritizes messages by their required velocity such that higher velocities imply higher

priorities. RAP provides a multi-layer communication protocol stack that co-operates on prioritizing packets at not only the network layer, but also at the MAC layer. Each packet is put to a different FIFO queue based on their requested velocity, i.e. the deadline and closeness to the gateway. This ensures a prioritization in the MAC layer. RAP as an architecture, is concerned about the physical geography of the network and distance plays a role in maintaining a desired speed or velocity across a sensor network. However, RAP does not provide a routing algorithm. Also RAP attempts on delay guarantees but energy metrics is not taken into consideration in the routing mechanism.

Akkaya and Younis [9] proposed a energy-aware approach for routing delay constrained data. This approach provides a multi-hop packet transmission thereby reducing the energy consumption at the nodes. Also, their approach employs weighted fair queuing (WFQ) packet scheduling methodology along with leaky bucket constrained data sources in order to provide soft real-time guarantees for data delivery. Such scheduling policy at each node provides a service differentiation between two different classes of traffic, namely real-time and non-real-time traffic. In the case of a mobile gateway, uninterrupted data flow for both types of traffic is achieved by dynamic adjustment of the route set-up to react to the gateway's departure out of transmission range of relaying nodes. The routing algorithm uses global knowledge of node queue sizes by the gateway to calculate end-to-end least cost paths and generate routing tables. In the same work, two different queues are proposed for prioritization of node packets. Use of such class-based, priority queuing mechanisms turns out to be expensive on resource limited sensor nodes and also does not include the delay caused by the MAC layer in routing delay constrained data.

Narasimhan and Kunniyur [10] proposed a framework to provide differentiated services over a sensor network by associating power with priority. All the data packets are routed by an underlying routing structure derived using any of the conventional

energy-efficient routing schemes. With the routing, every data packet at the source is associated with a power budget which indicates the total excess power that can be used by all nodes(in the routing path) to transmit that packet. The excess power actually indicates the difference in power consumption if the packet follows any other route. This associates a high priority to the packet with higher power budget. The nodes transmits the data packet with a higher power provided the total excess power that is consumed does not exceed the power budget of the packet. This ascertains that less delay is incurred by the packet with higher power budget. Initially the scheme employs topology control in deriving an optimal solution and uses an decentralized and randomized algorithm that approximates the optimal solution. Nevertheless, this scheme do not model the delays caused by channel access mechanisms.

CHAPTER 3

PROPOSED FRAMEWORK

3.1 Problem Formulation

3.1.1 Problem Definition

Let s be a sensor node generating time sensitive data to be sent to the sink τ as shown in figure 3.1; 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, $P^c = \{P_i | P_i \in P \text{ and } d_i \leq d'\}$.

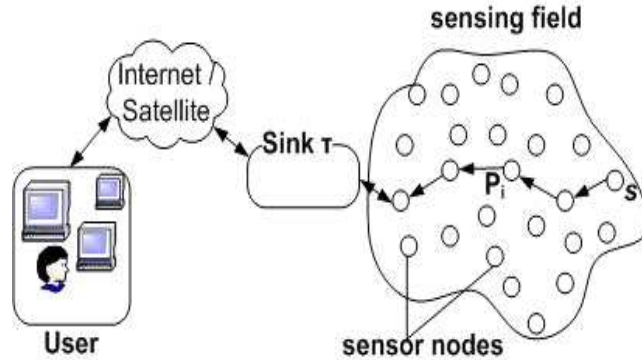


Figure 3.1: DCEERP Scenario

This problem belongs to the class of constrained path optimization problems and is NP-Complete [11]. Hence, heuristic solutions are feasible. Earlier heuristic provided to this problem [12] is applicable only under certain assumptions that restrict the

communication pattern among the sensor nodes. This thesis work aims to solve the DCEERP for more generalized communication patterns thereby allowing better utilization of network resources.

Measuring queuing delays in the network is not feasible due to the inconsistent traffic patterns in the sensor network field and hence our solution does not account for queuing delays in the network. Few other significant issues to be considered in proposing the DCEERP solution is i) the residual energy at the nodes and ii) reliability in data transfer.

3.1.2 Assumptions

Estimation of path delays in multi-hop wireless sensor networks using 802.11 like channel access schemes becomes cumbersome while using features like topology control. In order to arrive at the solution, few assumptions being made are as follows.

- The sensor nodes are assumed to be stationary in the network and are aware of their geographical location. There exist some locations services that facilitate such information [13] and does not require a GPS receiver at every node.
- 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. Such dual radio sensors are already being manufactured by Sensoria Corporation [14].

Since the 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. In order to make it energy-efficient, we also assume that the transmission power (and hence the range) of the long-range radios are adjustable.

- The sensor nodes use 802.11 like channel access scheme for each of the two wireless channels. A similar assumption is being made in [7, 8].

We present a network architecture and a routing framework in which the proposed approach enables us to model the channel access delays caused by the MAC layer and hence to arrive at the DCEERP solution.

3.2 Network Architecture

The geographical area over which the sensor nodes are deployed is divided into *sectors* of angular width θ and *annular bands* of thickness b as shown in figure 3.2. The

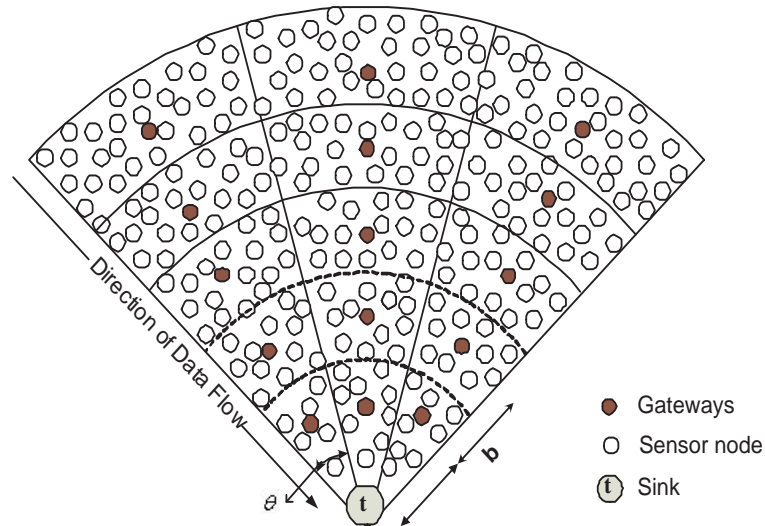


Figure 3.2: Network Architecture

activity region is viewed as a circular grid in polar co-ordinates, with the sink τ being at the center. The network grid is created when the sink advertises the values of θ and b over the entire network. As each sensor node is location aware, given the geographical scope of the cells, it associates itself with the grid cell it belongs to after the sink's advertisement. The nodes in each cell of the grid network can have one of the two status levels.

- **gateway**- a node that aggregates the information sensed and forms a communication infrastructure (backbone) with other gateways in the sector.
- **node** - a ordinary node.

Gateway Selection: Each cell in the network has a gateway - a node close to the cell's center that aggregates the information sensed by the nodes within that cell and forms a communication backbone with other gateways in the network. On hearing the sink's advertised values of θ and b , sensor nodes located within a small distance ϵ from a cell's center start a random timer(ϵ can be as small as $0.01b$ in dense networks). The node whose timer expires first advertises itself as the cell's gateway. On hearing this advertisement,the other nodes cancel their timers and elects the advertised node as the gateway. The direction of data flow is always from the gateway of respective bands toward the centralized sink.

The band closest to the sink has a thickness of $b + b/2$ and the gateways in this band are spaced at a distance of b from the sink. In the above architecture, each gateway is at a distance of $R = nb$, where n is the number of hops along the path to the sink.

3.3 Data Transmission Phases

In the above architecture, the information sensed is transmitted from source node s to the sink τ in two phases – *intra-cell* and *inter-cell* phase. In the former phase, the source node s directly transmits the sensed information to the gateway located in the same cell using its short-range radio. As the distance between the gateway and other nodes of the cell is limited, a direct transmission is possible. Since minuscule amount of nodes exist within a particular cell, we assume that the delay encountered in the intra-cell communication is d'' seconds, with $d'' < d'$ seconds. In the latter phase,a gateway relays the data to the sink τ within the remaining $d' - d''$ seconds either

directly or through other gateways in the sector. In the inter-cell phase, the gateways can transmit directly to the destination sink using long-range radios. However, in order to conserve energy, gateways select to relay data along multi-hop path. In this context, short-range radios are used for communication between neighboring gateways and long-range radios are used for communication between non-adjacent gateways.

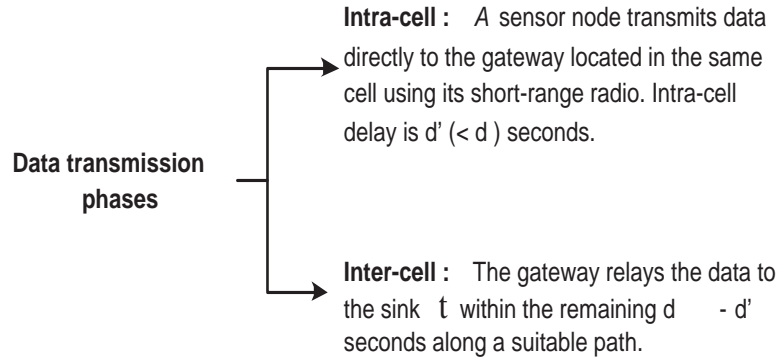


Figure 3.3: Data Transmission phases

The proposed heuristic solution finds an delay-constrained, energy-efficient path for the inter-cell phase of data transfer¹. Considering the gateway with adjacent sector gateways is feasible, providing various paths to the sink. However, it's makes the solution highly difficult in modeling the channel access delays. Hence, we streamline the communication pattern in the network in which the gateway acts as an intermediate hop only for the sensory data that originates in the same sector as the gateway.

As the gateways act as a representative in aggregating and relaying data from all nodes within the cell, their energy levels tends to drain earlier than other nodes. In such cases, the sink sends a RE-ELECT messages to all nodes within the cell and re-election of a new gateway takes place. It is also noted that the previously served gateways are inhibited from participation. Otherwise, the sink advertises different θ and b values for selection of a new gateway.

¹In the DCEERP solution, delay refers to the inter-cell delay.

CHAPTER 4

DCEERP SOLUTION

The main construct of the DCEERP solution is to firstly enumerate the set $\mathcal{P}_{g_{m,n},\tau}$ of all possible paths that exists between the source node $g_{m,n}$ and the sink τ . The energy consumed along every path is estimated and the paths in the set are indexed in the increasing order of energy consumption. Once the end-to-end delay along every path is estimated, we select the lowest indexed path that satisfies the delay constraint. Initially we assume that the sensor nodes in the network have sufficient energy for data transfer. However, in practical sense it is not possible. This factor is handled in later section of this chapter. Also, in estimating the transfer delay, reliability in data transfer is taken into consideration based on the probability of successful packet transmission.

4.1 Path Set Calculation

In calculating the path set, we use the k-shortest paths algorithm as described in [15]. The entire network is viewed as a directed acyclic graph with no directed cycles, i.e for any gateway $g_{m,n}$, there is no non-empty directed path starting and ending on $g_{m,n}$. The gateways are vertices with the links between two gateways as edges and their weights are equal to the energy consumption across the links.

Energy estimation across the links: In calculating the energy consumption (weights) of the links(edges), we consider a gateway g_n set at distance R meters from the sink and r_i as the distance between gateways g_i and g_{i-1} , with the sink being g_0 . 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 $\alpha \geq 2$ [16].

The k-shortest paths algorithm finds k-shortest paths from a given source gateway to sink with n vertices and m edges, in time $O(m + n \log n + k)$. The number of paths available for a gateway g_n is given by $N_P(n) = 2^n$ (exponential) and hence we use the k-shortest paths algorithm to enumerate the path set in polynomial time. The path set is divided into $N_P(n) \geq 2k$ paths and firstly we identify the first k-shortest paths. Now, to identify the other set of k-paths, we run the k-longest paths algorithm. The k-longest paths algorithm can be transformed into a k-shortest paths algorithm by negating all the edge weights and can solve it in the same time bounds. Thus, the path set $\mathcal{P}_{g_m, n, \tau}$ indexed in terms on energy consumption is obtained and delay across the paths in the set is then estimated.

4.2 Delay Estimation

The medium access delay across a wireless link is a function of the channel contention experienced by the nodes at either ends of that link. The terminologies used in this section are as follows.

- Let μ_n be the average time taken to transmit a packet from g_n to gateway g_{n-1} using the short-range radio. This includes both channel capture and transmission times, with propagation delays assumed to be negligible.
- μ'_n be the average time taken to transmit a packet directly from g_n to any other gateway or sink τ using the long-range radio.
- Let $T_{p,q}^n$ be the total time taken by a packet originating at g_n to reach g_q from g_p along the basis path using short-range links, where $p, q < n$ and $q < p$. Note that $T_{p,q}^n = \sum_{x=p}^{q+1} \mu_x$.
- $\mathcal{D}(g_n, g_{n-1})$ be the distance between two gateways g_n and g_{n-1} .

Once the values of μ_n and μ'_n are determined for all values of n , the delay across every path in the set can be estimated.

4.2.1 Short-range Delay

Consider a gateway g_n that transmits data to its neighboring gateway g_{n-1} using its short-range radio. Since the sensor nodes use 802.11 like channel access mechanism¹, the delay μ_n can be estimated if we can find the set of nodes I_n that interfere with g_n 's transmission to g_{n-1} [17]. A gateway g_{m_k, n_k} will interfere with $g_{m, n}$'s transmission to $g_{m, n-1}$ if either $\mathcal{D}(g_{m_k, n_k}, g_{m, n}) \leq b$ or $\mathcal{D}(g_{m_k, n_k}, g_{m, n-1}) \leq b$. The set of all such g_{m_k, n_k} 's constitute the set I_n . Since the short-range radio is the default and its reachability between neighboring gateways is set at b meters, set I_n is easily identified for each g_n . Using the set I_n , the values for μ_n can be estimated using the procedure outlined in [17].

4.2.2 Long-range Delay

Like in the short-range delay estimation, the delay μ'_n experienced in gateway g_n 's long-range radio transmission² can be estimated if the interference set U_n can be determined. Since the long-range radios are used only when necessary and that too with just enough power, it is not straight forward to estimate the interference set of long-range links.

Let N be the farthest band from the sink in the query region along any sector. If $T_{N,0}^N \leq d$, then all the gateways in the query region transmits data along their basis paths satisfying the delay constraint. In such cases, $U = \emptyset$ for all n . But, if $T_{N,0}^N > d$, then the gateways uses long-range radios in transmitting data to the sink.

¹In channel access mechanisms such as TDMA that are non-contention based, handling traffic fluctuations is not very flexible. They also have an overhead of schedule generation.

²Note that a gateway in the lowest band (band 1) is at a distance of b meters from the sink and does not use its long-range radio.

1. Determine I_n and estimate μ_n for all g_n using the procedure outlined in [17].
2. If $T_{N,0}^N \leq d$,
 - (a) The basis path $P_1 \in \mathcal{P}_{g_n, \tau}$ for a gateway g_n is its DCEERP solution.
 - (b) Return.
3. Else
 - (a) For each $n = 1 : N$,
 - i. $\mathcal{P}_{g_n, \tau} \leftarrow \mathcal{P}_{g_n, \tau} - \{P_i \mid P_i \text{ includes } T_{n,j}^n > d; 1 < j < n\}$
 - ii. Assign indices $i = 1 : x$ where $x < N_P(n)$ to paths $P_i \in \mathcal{P}_{g_n, \tau}$ such that for any $i < j$, there exist paths $P_i, P_j \in \mathcal{P}_{g_n, \tau}$ and $E_i < E_j$.
 - (b) Initialize : $\mathcal{U}_i \leftarrow \emptyset, i = 1 : n$ (for all gateways in the sector). Each element in set \mathcal{U}_i is of type (g_n, r_n, \mathcal{S}) . Here \mathcal{S} denotes a set of source gateways that uses g_n along their path.
 - (c) Repeat
 - i. For $n = N$ to 2,
 - A. For each index $i = 1 : x$ where $x < N_P(n)$
 - ① Estimate delay d_i using the current set \mathcal{U}_i and I_n using the procedure in [17] for lowest index path $P_i^* \in \mathcal{P}_{g_n, \tau}$ such that $d_i < d$.
 - B. For $k = N : 2$
 - ① $\mathcal{U}_k \rightarrow \mathcal{U}_k \otimes \{(g_j, r_j, \mathcal{S}) \mid j = 2 : N \text{ and } (g_j, r, \mathcal{S}) \text{ uses variable power or long-range in } P_i^*\}$. g_{k_R} is the reception node of g_k
$$\mathcal{U}_k \rightarrow \{ \mathcal{U}_k \cup \{(g_j, r_j, \mathcal{S})\} \mid |g_k - g_j| \geq r \text{ or } |g_{k_R} - g_j| \geq r_j$$
 - Until paths for all gateways do not change
 - (d) Return

Figure 4.1: Algorithm for solving DCEERP for a given delay constraint.

The iterative procedure of the algorithm in figure 4.1 simultaneously estimates the interference set U of long-range link and solves the DCEERP.

4.3 Other Consideration

Residual Energy : The solution takes into account the residual energy at each node in deciding the transmission path, therefore increasing the network lifetime. In the network, when the residual energy of any of the sensor node involved in the transmission path falls below a optimum value ω , all the current paths in the sector involving that particular node is annulled and the DCEERP solution is calculated again. It is also noted that the paths under consideration will not include any of the energy drained nodes.

CHAPTER 5

EXPERIMENTAL RESULTS

In this chapter, the proposed heuristic solution is evaluated for its efficacy and performance analysis is done by establishing the network scenario and performing numerical simulations. The performance of the proposed heuristic methodology (henceforth referred to as PRO-II) is evaluated and compared to the following routing schemes.

- Minimal energy path routing - MIN-EN: *MIN-EN* refers to the routing along the basis path of the set. This routing strategy curtails the amount of energy spent at the sensor nodes. However, the total delay involved in transferring data along this path can be more than the delay constraint.
- Direct Transfer - DIR: *DIR* refers to the direct long-range transmission of the gateways directly to the sink τ . Since there are no intermediate hops in the transmission, it leads to lower transmission delay at increased energy consumption.
- Direct Optimal-PRO : *PRO* refers to the routing strategy proposed in the earlier work [12]. In this strategy, the long-range radio links can directly transmit data to the destination sink τ alone and hence restricts the communication pattern. It also leads to higher energy consumption with mostly satisfying the delay constraint.

The performance of all the aforesaid routing schemes are compared based on the end-to-end delay incurred and energy expended in the inter-cell phase of data transmission. Results show that the proposed algorithm PRO-II provides an effective

balance in the network, thereby leading to a better performance when compared to other routing schemes.

5.1 Experimental Setup

Numerical simulations were carried out using MATLAB tool and simulation graphs obtained were used to compare the performance of all the routing schemes. The sensor activity region extends to a distance of 200 meters from the sink with an angular width of 180 degrees. The geographical expanse that generates periodic, delay-sensitive reports to the sink is restricted between the radii 0 to 200 meters. The band thickness b and angular width θ of the circular network are considered to be 20 meters and 30 degrees. The energy involved in transferring unit data over a distance of r meters is assumed to be proportional to r^α , with α taken as 3.8709 [16]. The link bandwidth is taken as 200 Kbps. The parameters of the 802.11 MAC protocol used in the simulation study are shown in table below.

Table 5.1: IEEE 802.11 Parameters

MAC Layer	Value
RTS(bytes)	44
CTS(bytes)	38
ACK(bytes)	38
Slot time(μsec)	20
SIFS(μsec)	10
DIFS(μsec)	50
Wmin	32
Wmax	1024

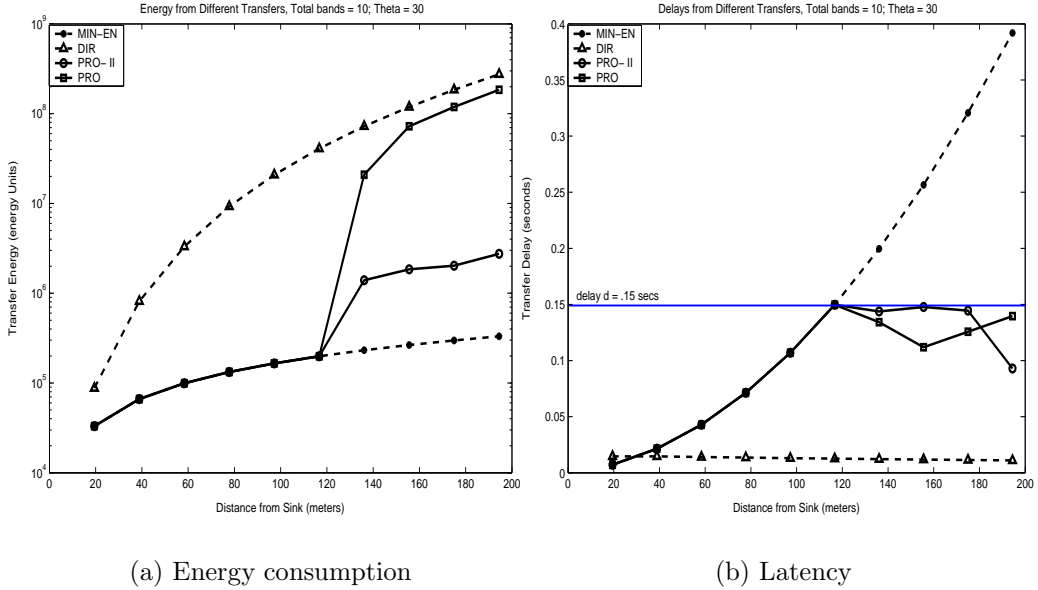


Figure 5.1: Performance of MIN-EN, DIR, PRO, PRO-II with respect to gateway location

5.2 Effect of the gateway location

In this section, we analyze the performance of the routing schemes based on the location of gateway nodes. The delay constraint taken in this experiment is 150 milliseconds(ms). Figures 5.1(a) and (b) depicts the energy expended and delay incurred in the data transmission from gateways located at various distance from the sink, under each of the four routing schemes. In case of MIN-EN scheme, we observe that both the energy consumption and transfer delay increases with increase in distance. This is obvious as the MIN-EN(basis) path from the gateway located farther away from the sink has more number of hops than other MIN-EN(basis) path from gateways closer to the sink. IN DIR scheme, we see that the energy consumption increases with distance similar to the claim in [16]. Also most of the energy is expended in communication than in sensing. However the transfer delay in DIR remains more or less unchanged. In DIR, the gateway(except the one closest to the sink) located anywhere in the query region transmits directly to the sink in a single hop using a long-range radio link. The delays involved in such a transfer is just

a single channel access plus a single transmission delay and this remains the same regardless of the gateway location.

In PRO, we see that that energy consumption and transfer delay follows that of MIN-EN up to a certain distance(120 meters in this case), and then takes a diverted route. This is because whenever the MIN-EN(basis)'s path satisfies the delay constraint, PRO considers it as the minimum energy path. When the basis path does not satisfy the delay constraint(in the above scenario, this happens for gateways beyond the distance of 120 meters) PRO chooses a minimum energy path that involves a direct long-range transmission to the sink. Since the chosen path involves a direct long-range transmission, gateways located located farther away from the sink incurs high energy consumption. Similar to PRO, PRO-II follows the MIN-EN up to a certain distance(120 meters in this case) after which it choses a minimum energy path as stated in the algorithm. In PRO-II, the MIN-EN(basis) path is chosen whenever it satisfies the given delay constraint as the MIN-EN path consumes the least energy of all other paths. When the MIN-EN path does not satisfy the delay constraint, PRO-II choses the next least energy path from the path set. Unlike in PRO, the path chosen does not necessarily transmit directly to the sink in one hop using a long-range radio link. Instead, the PRO-II transmission involves a mix of long and short range transmission. Hence the transfer delay in PRO-II in lesser when compared to PRO and other routing schemes. This clearly shows the PRO-II scheme provides a better performance satisfying the delay constraint with minimal energy consumption.

5.3 Effect of the delay constraint

We now consider the performance of all the four routing schemes with respect to various delay constraints and the graphs in figures 5.2(a) and (b) show their performance. Here, we consider only the farthest gateway in the query region to measure the energy

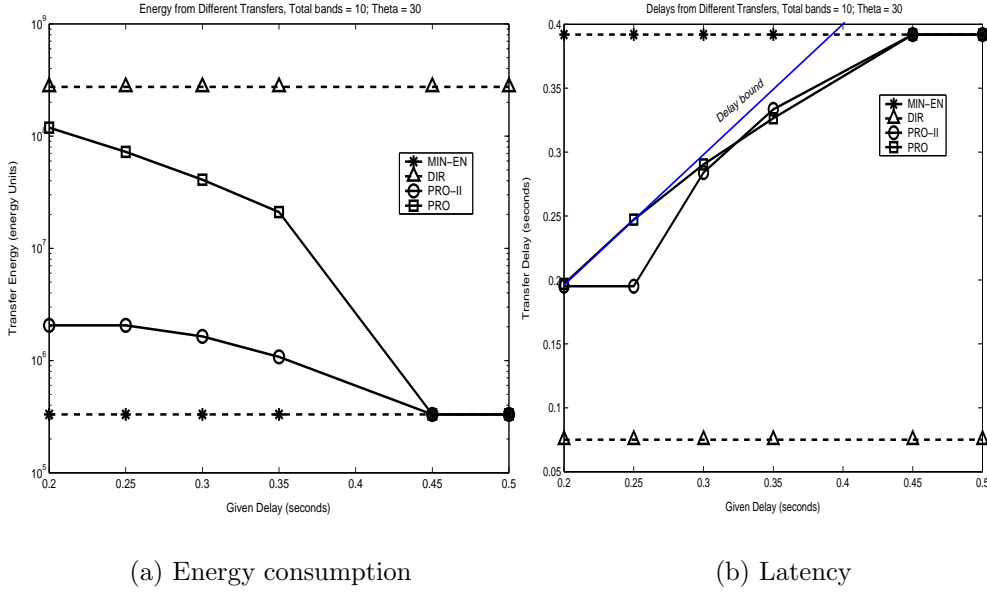


Figure 5.2: Performance of MIN-EN, DIR, PRO, PRO-II with respect to given delay constraint

consumed and delay incurred in data transmission as it is the limiting case. We can notice from the graphs that the performance of MIN-EN and DIR is unchanged for any delay constraint. This is because the routes in both the schemes are calculated independent of the delay constraint. MIN-EN scheme utilizes lesser energy and takes the basis path, thus satisfying only large delays. DIR however, satisfies the delay constraint at the expense of higher energy consumption. PRO and PRO-II performance alters perceptibly with varied delay constraints. The delay constraints are always satisfied by both the routing schemes at the expense of energy. Both schemes follows the MIN-EN route for large delay constraints and hence consumes less energy. For stringent delay values (for delays less than 450 ms in this case), they bend towards the DIR scheme. This is because, as said earlier, PRO and PRO-II route data via the MIN-EN path with multiple short-range transmissions for loose delay constraints. But for smaller delay constraints, the gateways minimizes the number of intermediate hops by using long-range transmissions. Hence the energy expended is also high. While PRO tends to use a single long-range directly to the sink from the node after

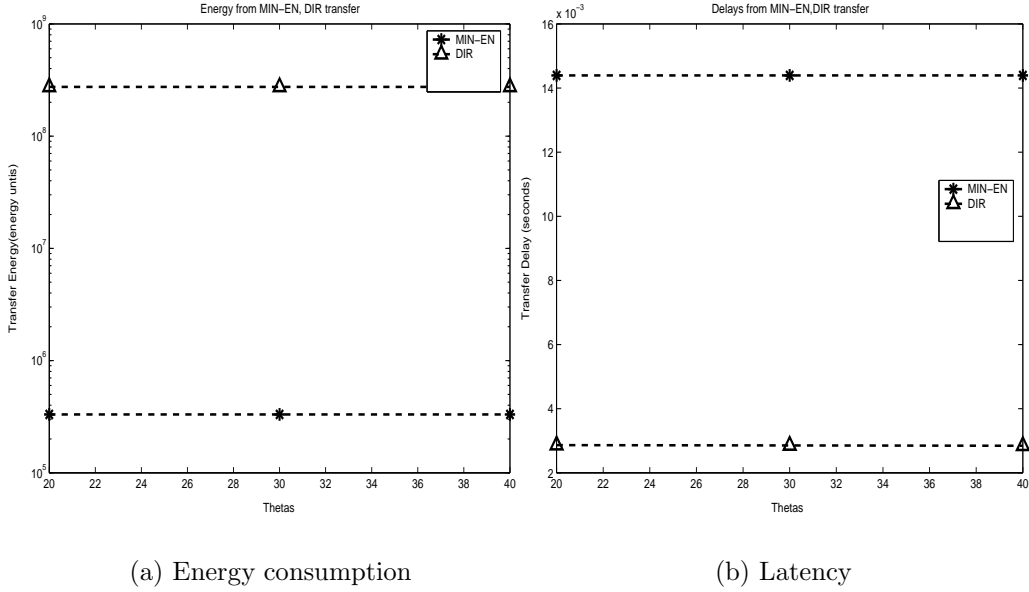


Figure 5.3: Influence of θ on the performance of MIN-EN and DIR

which the delay constraint is not satisfied, PRO-II tends to use several short and long-range combinations thereby reducing the long-range transmission distance. This may result in negligible increase in delay, but reduces the amount of energy involved in the transmission. So, PRO-II surpasses PRO and other's performance by reducing the energy involved in the data transmission.

5.4 Effect of parameter θ

In the network architecture, the activity region is divided into sectors of angular width θ and annular bands of thickness b . Thus both θ and b may have a significant impact on the performance of all the four routing schemes. In this section, we consider the effect of the angular width θ of the network in the behavior of all the routing schemes. Each of the routing schemes choose different path based on the delay requirements. The path chosen for data transmission belonging to the path set consists of gateway nodes within the same sector as the source node. Since the band thickness b is fixed, any variations in θ may not alter the path set. However, change in band thickness along with θ may result in more bands in the sector.

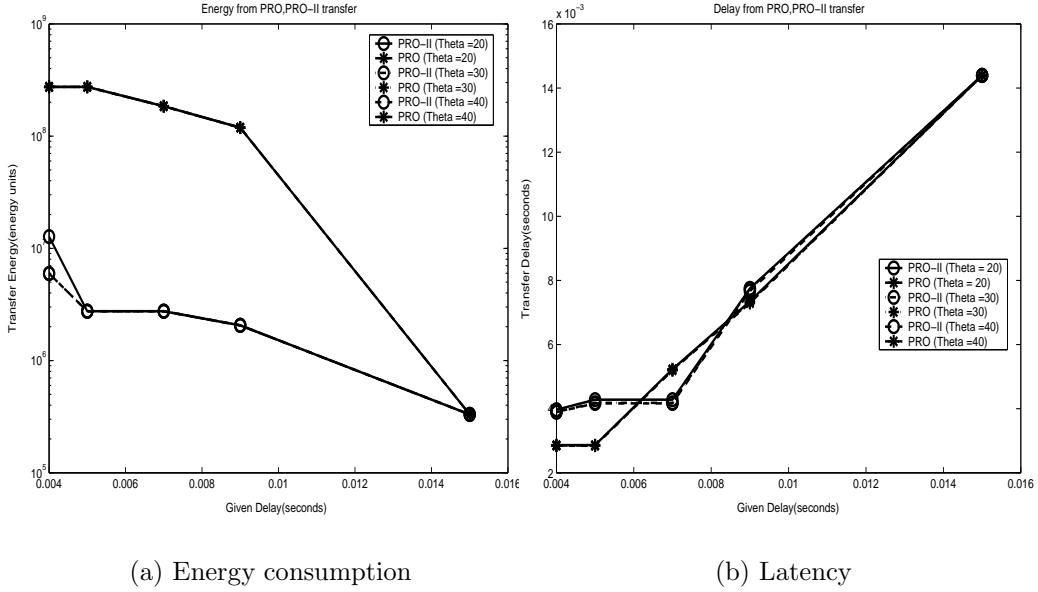


Figure 5.4: Influence of θ on the performance of PRO, PRO-II

The number of nodes that may interfere with a gateway node's transmission may increase/decrease based on θ variations. This may affect the delay estimation depending on the change in the interference set. Consequently, the path taken by PRO and PRO-II may differ. However, graphs in figures 5.3 and 5.4 show that θ variations have minimal effect on the performance of all four routing schemes. To summarize, variation in the angular width θ does not influence the performance of MIN-EN, DIR, PRO and PRO-II with respect to both transfer energy and transfer delay.

5.5 Effect of parameter b

We now analyze the influence of parameter b on the routing performance. We analyze the energy consumption and delay incurred by all the four routing schemes with respect to the father gateway in the activity region.

Figures 5.5 and 5.6 depicts the energy expended and delay incurred in the data transmission under all the four routing schemes with respect to varying number of bands. In graph 5.5 (a), we can notice that transfer energy under DIR remains unchanged with increase in number of bands. But MIN-EN scheme's energy con-

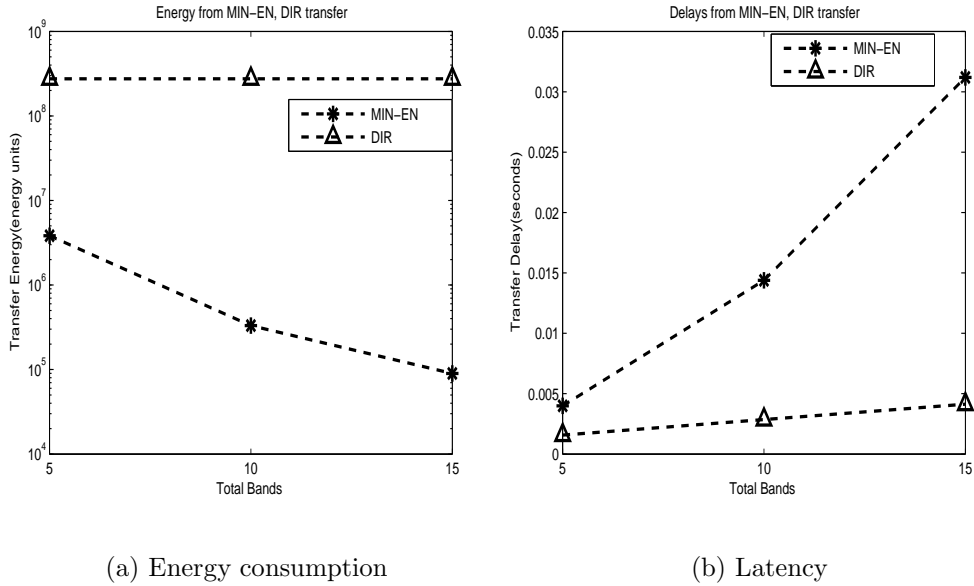


Figure 5.5: Influence of number of bands on the performance of MIN-EN and DIR

sumption decreases with increase in number of bands. This happens because under DIR, the energy consumption is based on the distance of the farthest gateway from the sink node and hence change in number of bands or change in band thickness b does not affect the amount of energy consumed by the source gateway node. The behavior of the MIN-EN scheme can be explained as follows. When we increase the number of bands, the band thickness b decreases. This in turn, reduces the single hop distance between two gateway nodes and the MIN-EN(basis) path contains more number of hops to the sink. Since the energy required to transmit data over single hop is proportional to b^α , overall energy consumption by the nodes in the MIN-EN path is reduced. Now considering the graph 5.5 (b), we can see that under DIR, there is a slight increase in the end-to-end transfer delay. Though the DIR transfer is only a single hop long-range transfer, the increase in number of bands certainly increases the number of gateways in the network. This results in more gateways competing for channel access and there is a increase in channel capture time. Hence the observation. In MIN-EN scheme, as said before, there is increase in number of hops in the MIN-EN path. This results in more number of channel access by the gateway nodes and hence

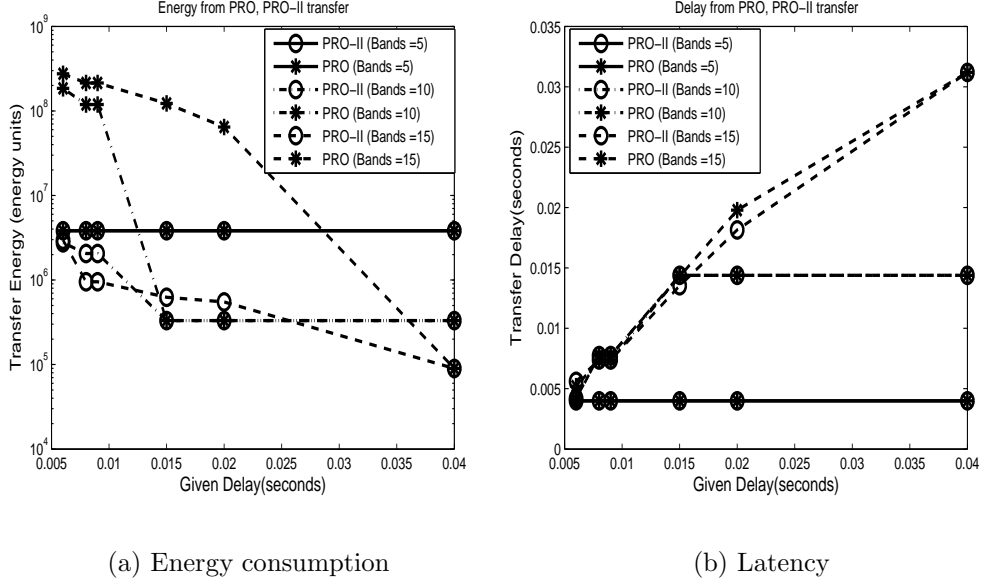


Figure 5.6: Influence of number of bands on the performance of PRO, PRO-II

the end-to-end transfer delay increases.

In graphs 5.6 (a) and (b), we can see that under PRO, increase in number of bands increases the transfer energy for strict delay constraints. However, the same increase in band number decreases the transfer energy for loose delay constraints. The same performance is experienced by PRO-II, however the transfer energy consumption is much lesser. PRO-II paths have a mix of long-range and short-range link and hence the observation. PRO, PRO-II and MIN-EN follow the same path, when the MIN-EN(basis) path can satisfy the delay constraint. When the MIN-EN path does not satisfy the delay constraint(which happens for strict delays), then PRO uses long-range transmissions by the gateways directly to the sink. The data from the farthest gateway in the sector is brought less closer to the sink along the MIN-EN path, when there are more bands in the network¹. Consequently, when PRO uses a gateway's long-range transmission, the distance over which the gateway transmits is comparatively longer with more number of bands. This results in higher energy consumption for strict delays under PRO scheme. The same rationale is applicable

¹With increase in number of bands, the per hop length is small

to PRO-II, however the energy consumption under PRO-II is much lesser due to the availability of more paths between the source and destination. In both schemes, data is transmitted along the MIN-EN(basis) path over long distance and hence there is no use of long-range transmissions. This obviously reduces the energy consumption by the gateway nodes. Hence the observation.

CHAPTER 6

CONCLUSION

6.1 Summary

In Wireless Sensor Networks(WSNs), energy consumption and delay guarantee issues are of major consideration in developing efficient routing schemes. Due to the increasing number of applications of such networks, many such efficient routing schemes were proposed. However, any routing scheme that does not consider the delay caused by the MAC layer in data transmission is considered inadequate. As the wireless medium is broadcast in nature, the delay introduced by the MAC layer in capturing the channel can be considerable, especially along a multi-hop path. Hence, a unique approach in handling the MAC delay metric in finding energy efficient routing paths for delay sensitive applications is of high concern.

In this thesis work, a novel solution is proposed for finding energy-efficient paths that satisfy the delay constraints in sensor networks. The proposed network architecture in conjunction with the routing framework enables us to model the delays caused by the 802.11 like MAC protocols. This in turn, allows us to obtain better estimates for the end-to-end delays of the paths. Experimental results show that the proposed solution is effective in satisfying the delay constraint and also reduces the energy consumption in data transmission compared to conventional solutions. Also, the proposed solution is compared to our previous work [12] which is applicable only under certain assumptions that restrict the communication pattern among the sensor nodes. This thesis work solves the DCEERP for more generalized communication patterns thereby allowing better utilization of network resources.

6.2 Further Consideration and Future Work

This work proposes a new protocol and hence more work will certainly improve the results much better. Few considerations are as follows

- The main consideration is to handle the network scalability issue. As the network grows, the cell area increases and hence a direct communication may not be possible within the cell.
- In estimating the delay across the path ,the intra-cell phase delay is assumed to be negligible. However, including the intra-cell delays will provide a much approximate delay incurred in the link.

A good balance achieved between the latency incurred in the data transfer and energy consumption makes the protocol highly efficient and along with the above mentioned considerations, the proposed protocol can serve as an ideal choice for highly delay sensitive WSNs applications

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The advances of wireless technologies at a rapid pace along with sophisticated embedded computing systems have led to the emergence of un-attended Wireless Sensor Networks (WSNs). Regardless of the energy limitations in the sensor nodes; WSNs have enabled a plethora of new services and applications. While several energy efficient routing protocols have been proposed to address the energy limitations of the sensors, they tend to increase the end-to-end delay involved in data transmission to the control center. This leads to the Delay-Constrained, Energy-Efficient Routing Problem (DCEERP) in many WSNs applications.

This thesis work proposes a novel energy efficient routing strategy to solve DCEERP that employs topology control and also models the channel access delays caused by 802.11 like MAC layers. This in turn, allows us to obtain better estimates for the end-to-end delays of the paths. Experimental results show that the proposed solution is effective in satisfying the delay constraint and also reduces the energy consumption in transmission when compared to conventional solutions. Also, the proposed solution solves the DCEERP for more generalized communication patterns thereby allowing better utilization of network resources.

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