Base-Station Repositioning For Optimized Performance of Sensor Networks

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Abstract

Most of the energy aware routing approaches for unattended wireless sensor networks pursue multi-hop paths in order to minimize the total transmission power. Since almost in all sensor networks data are routed towards a single sink (base-station), hops close to that sink become heavily involved in packet forwarding and thus their batteries get depleted rather quickly. In this paper we investigate the potential of base-station repositioning for enhanced network performance. We address issues related to when should the base-station be relocated, where it would be moved to and how to handle its motion without any effect on data traffic. Our approach tracks the distance from the closest hops to the base-station and the traffic density through these hops. When a hop that forward high traffic is further than a threshold the base-station qualifies the impact of the relocation on the network performance and moves if the overhead is justified. The presented approach is validated in a simulated environment.

1. Introduction

Networking unattended wireless sensors is expected to have significant impact on the efficiency of many civil applications, such as disaster management, environment monitoring and security [1][2][3]. Sensors are generally equipped with data processing and communication capabilities. The sensor sends its collected data, usually via radio transmitter to a command center either directly or through a base-station (gateway) Fig.1. The gateway can perform fusion of the sensed data in order to filter out erroneous data and anomalies and to draw conclusions from the reported data over a period of time.

Fig. 1: Three-tier sensor network architecture

Sensors are tiny energy constrained devices, hence energy has to be managed wisely in order to extend the life of the sensors for the duration of a particular mission. Energy efficient data routing in wireless networks generally pursues multi-hop paths in order to minimize the total

transmission power which is generally proportional to distance squared or even higher in order for environment rich with obstacles and interference sources. The basic idea of multi-hop network paths is to shorten the distance so that significant power savings can be achieved.

Since almost in all sensor networks data are routed towards a single sink, the gateway in our model, hops close to that sink become heavily involved in packet forwarding and thus their energy resource gets depleted rather quickly. The hops that are further away from the gateway have to be used as substitutes. Such scenario increases total transmission power and gradually limits sensor coverage in the network and eventually makes the network useless. If the gateway has limited motion capability it will be desirable to relocate the gateway close to an area of heavy traffic or near loaded hops in order to decrease total transmission power and extend the life of nodes on the path of heavy packet traffic. Additionally, this will reduce the average delay per packet. An example of this scenario is when the gateway is a laptop computer or other portable devices with a rescue crew who is not expected to walk long distances.

Relocating the gateway during regular network operation is very challenging. The basic issues are when it would make sense for the gateway to be relocated, where the gateway should go and how it will be moved. The relocation of the gateway first has to be motivated by odd pattern of energy depletion or data route setup, even if it is the most efficient network operation given the traffic distribution and network state at that time. Once the gateway detects such odd pattern it identifies the best location to be placed at in order to enhance network performance. While the gateway is on the move, it must ensure that no data is lost during that period. The gateway performs a trade-off analysis between the gain achieved by going to a new location and the overhead in terms of additional energy consumption that the relocation imposes on sensors. If the relocation is justified, the gateway moves towards that location.

In this paper, we study the three issues of when, where and how to relocate the gateway node. Repositioning the gateway is a very complex problem, NP hard in nature, given the infinite number of locations that the gateway can move to. Therefore, we pursue a heuristic search that is based on the current network topology and traffic pattern. We use the traffic density times the transmission power as metric for monitoring network performance and searching for the best gateway location. Our approach tracks the changes in the nodes that act as the closest hop to the gateway and the traffic density going through these hops. If

the distance between the gateway and some of the nodes that are in direct communication is larger than a threshold value, the gateway will qualify the impact of these nodes on the overall network lifetime by considering the number of packets routed through them. If the transmission power times the traffic density is large enough the gateway will consider relocating to a new position. The gain for the potential relocation is further qualified against the overhead imposed by the relocation on sensor nodes. To the best of our knowledge, the issue of gateway relocation has not been addressed in the literature.

In the balance of this section, we describe our system model and survey related work. Section 2 presents our approach for triggering and handling the gateway relocation. Section 3 is dedicated for the experimental validation of the presented approach and analyzing performance results. Finally, we conclude the paper in section 4 with a summary and point out our future research directions.

1.1 System Model

A set of sensors is spread throughout an area of interest to detect and possibly track events/targets in this area. They are battery-operated and are empowered with limited data processing engines. A significantly less energy constrained gateway node than all the sensors, is deployed in the physical proximity of sensors. It is assumed to know the geographical location of deployed sensors. Gateway is responsible for organizing the activities at sensor nodes to achieve a mission, fusing the collected data, coordinating communication among sensor nodes and interacting with the command node. The system architecture of sensor network system is depicted in Fig.1

While sensor nodes are stationary, we are considering a model for a gateway with limited mobility. The gateway remains stationary unless the network operation becomes inefficient. The gateway tries to relocate to another position in order to optimize some performance metrics, e.g. maximizing network lifetime. Sensors are assumed to be within the communication range of the gateway node. The sensor is assumed to be capable of operating in an active mode or a low-power stand-by mode. Both the radio transmitter and receiver can be independently turned on and off and the transmission power can be programmed for a required range. A sensor can act as a relay node to forward data. It is worth noting that most of these capabilities are available on some of the advanced sensors [4].

1.2 Related Work

Energy-aware routing has received significant attention in recent years, motivated by advances in wireless mobile devices. A comparison between different energy-aware routing protocols is conducted in [5][6]. Achieving energy saving through activation of a limited subset of nodes in an ad-hoc wireless network has been studied in SPAN [7], GAF [8] and ACSENT [9]. On the other hand, various energy-aware routing protocols for sensor networks have been developed. Some of these protocols followed data

centric routing approach where meta-data is exchanged before actual data is transmitted [10][11]. To cope up with the additional load in sensor networks, network clustering has been pursued in some routing approaches [5][12][13]. Location based protocols [14] and flow-based protocols have also been developed [15].

While the goal of most published techniques is to increase network lifetime through clever architecture and management of the network, none of the work addresses the possibility of relocating the sink (gateway) node for increasing network lifetime.

2. Gateway Relocation for Increased Efficiency

Although the energy-aware multi-hop routing, e.g. [13], does dynamically adapt to changes in sensor's energy and traffic pattern, the lifetime of the network is shortened due to a spiral pattern of energy depletion as stated in section 1. In order to enhance the system lifetime, we propose a limited motion to the stationary gateway towards the sources of largest traffic. Such approach has multiple advantages. First, the gateway will be near to nodes collecting maximum data, thus reducing communication-related energy consumption. It is thus expected that the average energy per packet to be reduced. In addition, the overall latency time for data collection will be lower. Moreover, the packet throughput will be higher since it is expected that messages pass through fewer hops and travel shorter distances making them less likely to be dropped.

To achieve such performance gains, one needs to address the basic questions of when to relocate the gateway, where to place it and how to handle data traffic during the transition. In this section we address these three issues.

2.1 When to Move the Gateway

The decision for a gateway movement has to be based on an odd pattern in route setup. Once the gateway detects that pattern it will consider relocation. Such consideration does not necessarily lead to an actual relocation. The gateway qualifies the impact of the potential new location on the quality of the route setup, measured in some static metric. If the impact is positive, the gateway starts to move. Therefore the "When" and "Where" issues of the gateway movement are very closely inter-related. The following notations are used for considering gateway relocation:

G: Gateway in a cluster.

G₁: Set of sensors less than distance D from G

G_R: Set of sensors that are one hop away on the active route.

G_{R1}: Set of sensors in G_R which are also in G₁, i.e. $G_{R1} = G_1 \cap G_R$

G₁^{new}: Set of sensors less than distance D away from the gateway at the new location.

G_R^{new}: Set of sensors those are one hop away on new route at the new location.

G_{R2}: Set of sensors in G_R^{new} which are also in G₁^{new}, i.e. $G_{R2} = G_1^{new} \cap G_R^{new}$

P_i: Packet traffic measured as the number of packets per frame, going through a node.

PT: Set consisting of packet traffic of each sensor in G_{R1} in an ascending order

PT^{new}: Set consisting of packet traffic of each sensor in G_{R2} in an ascending order

E_(Tri): Energy consumed by a node i in transmission of a packet to the next hop.

Note that G_I^{new} , G_R^{new} , G_{R2} and PT^{new} are calculated by placing the gateway at new location. The basic idea is for the gateway to check the changes in data paths in consecutive routing cycles. Typically re-routing is performed in response to a high packet loss caused by the energy depletion or failure of a relay node or is triggered by a change in data sources that requires setting a new topology [13]. When comparing routes in two consecutive cycles, if the data sources are the same and the nodes in previous G_{R1} differs from that the current G_{R1} , the gateway perform further analysis. The gateway checks the nodes that used to be in the previous G_{R1} and are excluded from the new G_{R1} . If these nodes were among the bottom 70% of the set PT , relocation would not be necessary. On the other hand if these nodes were forwarding high traffic (among top 30% in PT), the gateway perform a heuristic search for a better position.

To qualify the impact of placing the gateway at a new position, some static network performance metric has to be used. Most of the popular performance metrics for sensor networks, such as average delay per packet and throughput, are based on the network operation over a period of time and are typically network-wide in scope. Therefore, we use as a metric the total transmission energy of the relay node that are one-hop away from the gateway, basically those in G_R and G_R^{new} . A positive impact on the total transmission energy for these nodes would be a good indication for the gateway move. However, the reduction in the total transmission energy has to exceed an application threshold to justify the overhead, as discussed later in this section. A constant δ can be derived based on the overhead for handling the motion both at the gateway and at the network level. The condition for relocation can be mathematically defined as:

$$\sum_{\forall i \in G_R} E_{(TR_i)} \times P_i - \sum_{\forall j \in G_R^{new}} E_{(TR_j)} \times P_j > \delta$$

As mentioned earlier, finding an optimal new location for the gateway is an implicit issue for the relocation decision. Optimal placement of the gateway is an NP-hard problem in the general term. Therefore we pursue a heuristic search and settle for a quasi-optimal location to overcome such complexity. In the next subsection we explain such heuristic approach.

2.2 Where to Move the Gateway

Once we decide the gateway movement, the complex problem of determination of direction of motion for G could be based on the on the network traffic. The idea is to move G towards the sensors that generate the most number

of packets. However, it may be infeasible for G to go that far from its current position, e.g. due to limited mobility resources. The network topology changes dynamically and thus there is a risk for wasting substantial resources for reaching a far position, which turns shortly after to be not optimal due to changes in the environment. To achieve similar effect, we try placing G close to the relay nodes in G_R , which routes the largest number of packets. To identify such relay nodes, the list PT is consulted and the top nodes on the list are picked as candidates.

In our approach, G is to move towards the most dominating node in PT , whichever gives a greater value of δ . In case multiple relay sensors in the top part of PT share that dominance, a weighted average based on the distance between the gateway and these relay sensors and their traffic density is taken into account. The idea is to balance the gateways interest while picking the direction of the move.

A position “g” equidistant, in terms of distance $\times$ traffic density, from the relay sensors on the different high traffic paths is calculated. While such repositioning will be ideal for high traffic paths, it can worsen the total power consumed on other paths with lower traffic density. Therefore, the gateway will be placed on some point on the straight line between its current position and the newly calculated position “g” that is equidistant from picked relay nodes.

Fig.2: G balances its interest in serving nodes A and B while deciding how far should it travel in that direction.

Fig. 2 illustrates how to pick the direction of the gateway movement to optimize total transmission energy for the top two relay nodes in PT . Balancing the interest of the relay node A and B changes the slope of the gateway travel path. However, placing the gateway at position g on the line between A and B increases the efficiency of packet transmissions from A and B to the gateway at the expense of node C. Therefore a position on the path to g that minimizes the total transmission energy for the entire G_R set will be looked for using a bisection search.

2.3 Handling Gateway Motion

Once the new location of the gateway has been picked and confirmed to enhance performance of the sensor network, a plan for moving the gateway without losing the packets destined to it has to be generated. In order to handle this problem, we move the gateway during the routing phase of the utilized algorithm. The underlying routing approach has different phases, namely data transfer phase and routing phase. In the data phase, each sensor node sends data packets to the gateway using its routing table. On the other hand, in the routing phase, the sensors send their information to the gateway and based on such information multi-hop routes to the gateway are created and routing table information is sent back to the sensor nodes. Since no data packet is being transmitted during this phase, gateway relocation can be easily done by changing the position of the gateway followed by the modification of network topology at the new position without any effect on data transfer.

3. Experimental Validation

The effectiveness of repositioning the gateway is validated through simulation. This section describes the performance metrics, simulation environment, and experimental results.

3.1 Performance Metrics

We used the following metrics to capture the performance of our approach:

- *Time for first node to die*: This metric gives the time instant when the first sensor node runs out of energy, which reflects the time for network partitioning.
- *Time for last node to die*: This metric along with time for first node to die metric, gives an indication of network lifetime.
- *Average lifetime of a node*: This gives a good measure of the network lifetime.
- *Average delay per packet*: Defined as the average time a packet takes from a sensor node to the gateway.
- *Average energy per packet*: This metric represents the average energy consumed in transmitting, and receiving a data packet.
- *Network Throughput*: Defined as the total number of data packets received at the gateway divided by the simulation time.

3.2 Environment Setup

In the experiments the network consists of 100 randomly placed nodes in a 500×500 meter square area. The gateway position is determined randomly within the network boundaries. A free space propagation channel model is assumed with the capacity set to 2Mbps [16]. Packet lengths are 10 Kbit for data packets and 2 Kbit for routing and refresh packets. Each node is assumed to have an initial energy of 5 joules. The buffers have default size of 5 packets [17]. A node is considered non-functional if its energy level reaches 0. The routing approach in [13] is used to set the sensor states and multi-hop routes to the gateway.

For a node in the sensing state, packets are generated at a constant rate of 1 packet/sec. This value is consistent with the specifications of the Acoustic Ballistic Module from SenTech Inc. [4]. Each data packet is time-stamped when it is generated to allow the calculation of average delay per packet. In addition, each packet has an energy field that is updated during the packet transmission to calculate the average energy per packet. A packet drop probability is taken to be 0.01. This is used to make the simulator more realistic and to simulate the deviation of the gateway energy model from the actual energy model of nodes. We assume that the network is tasked with a target-tracking mission in the experiment. The initial set of sensing nodes is chosen to be the nodes on the convex hull of sensors in the network. The set of sensing nodes changes as the target moves. Since targets are assumed to come from outside the cluster, the sensing circuitry of all boundary nodes is always turned on. The sensing circuitry of other nodes are usually turned off but can be turned on according to the target movement. Targets are assumed to start at a random position outside the convex hull. Targets are characterized by having a constant speed chosen uniformly from the range 4 meters/s to 6 meters/s and a constant direction chosen uniformly depending on the initial target position in order for the target to cross the convex hull region. It is assumed that only one target is active at a time. This target remains active until it leaves the deployment region area. In this case, a new target is generated.

3.3 Performance Results

In this section we present some performance results obtained with and without repositioning the gateway. In order to see the effect of repositioning the gateway on energy consumption, we looked at the average lifetime of a node, time for first and last node to die and average energy consumed per packet. The results depicted in Fig. 3 and 4, have shown that our approach of repositioning the gateway decreases energy consumption significantly especially by increasing the average lifetime of the node and time for first node to die. In this approach, since the gateway is relocated close to heavily loaded nodes, less energy is consumed for

Fig. 3: Comparison of lifetime of nodes for two approaches

Fig. 4: Comparison of average energy per packet for both the approaches

Fig. 5: Comparison of throughput and delay for two approaches

communication thus leading significant amount of energy savings. On the other hand, the latency of the packets from those nodes to the gateway will be decreased, causing the average delay per packet to decrease drastically. There is also a slight increase on the throughput due to smaller packet drop probability since packets travel shorter distances (See Fig. 5).

4. Conclusion and Future work

In this paper, we presented a repositioning approach for a gateway in order to enhance the overall performance of a wireless sensor network in terms of popular metrics such as energy, delay and throughput. The presented approach considers relocation of the gateway by checking the traffic density of the nodes that are one-hop away from the gateway and their distance from the gateway. Once the total transmission power for such nodes is guaranteed to reduce more than a certain threshold and the overhead of moving the gateway is justified, the gateway starts to move to the new location. The gateway is moved in the routing phase so that the packet relaying will not be affected. Simulation results have shown that such repositioning of the gateway increases the average lifetime of the nodes by decreasing the average energy consumed per packet. Moreover, the average delay per packet is decreased significantly.

As a future work, we plan to extend the approach so that it will allow transmission of packets during movement

of the gateway even if the gateway goes out of the transmission range of the nodes. Furthermore, we plan to work on repositioning the gateway under QoS traffic in order to provide better QoS.

5. References

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