Rate-Constrained Data Aggregation in Power-Limited Multi-Sink Wireless Sensor Networks

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***Abstract*—We propose a cross-layer data-aggregation approach that maximizes the lifetime of wireless sensor networks with multiple sinks while ensuring the feasibility of the routing solution. The proposed approach accounts for the coupling effects between MAC- and network-layers to ensure the physical feasibility of the obtained solutions, and maximizes the network lifetime by avoiding nodes with critical energy resources. Using simulations, we demonstrate the impact of not including medium access contention constraints in the routing formulation on the physical feasibility of the routing solution. We also study the impact of several network parameters on the network lifetime.**

***Index Terms*—Cross-layer design, data aggregation, energy-efficient routing, wireless sensor networks.**

I. Introduction

Wireless sensor networks (WSNs) consist of a large number of battery-powered sensor nodes that are capable of sensing, processing, and gathering data from surrounding environments and transmitting it to a data collector called a sink. Sensor nodes are typically randomly deployed in the area of interest, and nodes can sense/measure various kinds of things, such as temperature, humidity, lightning condition, and pressure [1]. Examples of WSN applications are environment monitoring, military, health-care, building surveillance and safety, and many others [1], [2].

WSNs have unique characteristics, giving rise to new requirements and challenges when designing routing and data collection approaches. We next discuss three key design requirements and objectives that need to be accounted for when designing routing techniques: reducing energy consumption, avoiding contention bottleneck, and ensuring data rate feasibility.

Energy consumption: Sensor nodes have limited computational, storage, and transmission power capabilities. Their energy resource limitation is due to the fact that they are typically battery powered, and it is usually not possible to replace/recharge batteries (as sensors can be deployed in harsh environments, making it too difficult to access them). Therefore, battery resources should be handled efficiently when designing WSN techniques in order to save energy and maximize network lifetime.

Contention bottleneck: In WSN applications, sensed data generated by sensors needs to be sent to sinks (one or a few) whose resource capabilities are usually better than the sensors. Due to their power limitation and design nature, sensors have small sensing and communication ranges, and as a result, they rely on multi-hop communication to send their sensed data to their sinks. This type of communication creates unbalanced contention across different neighborhoods. That is, sensors located in close vicinity to sinks tend to communicate more traffic than others, thereby leading to a fast depletion of their energy resources. This in turn rises some connectivity issues. One way to alleviate this problem is by increasing the number of sinks.

Data rate feasibility: There have been many efforts that aimed to develop routing schemes that maximize lifetime in WSNs with single sink (SS-WSNs) [3]–[6] and multiple sinks (MS-WSNs) [7]–[10]. However, even though the existing routing approaches reported in the literature are energy efficient, the majority of these approaches perform network layer optimization and ignore the effect of underlying medium access control (MAC) contention associated with the shared wireless medium. As a consequence, the number of flows routed through nodes in the same neighborhood may be such that the shared medium may not be able to provide the data rates required to support these flows. As a result, the data rate requirements of the traffic flows cannot be satisfied by the network, and therefore, the routing solution may be unfeasible. It is therefore important to design routing schemes that account for cross layer effects so as to ensure solution feasibility.

In this paper, we propose a MAC-aware, energy-efficient data aggregation scheme for MS-WSN traffic with rate constraints. We use sufficient conditions proposed in [11] to ensure physical feasibility of the obtained routing solutions. We follow a routing formulation approach similar to that used in [12], where the difference lies in that this formulation considers multiple sinks instead of only one sink as done in [12]. The routing problem is formulated as a linear program whose objective function is to maximize the network lifetime. We use this formulation to also study the performance of our routing approach in terms of solution feasibility and network lifetime.

The rest of this paper is organized as follows. Section II presents the related work. In Section III, we describe our network model. Section IV presents the proposed routing technique. We then, in Section V, study the performance of our routing approach. Finally, we conclude the paper in Section VI.

II. Related Work

Numerous routing techniques have been proposed for SS-WSNs with an emphasis on energy consumption. For example, in [4], the authors formulated a routing problem for maximizing the network lifetime as a linear programming problem where the main objective was to determine the optimum total amount of flow for each link. By solving this linear programming problem, an upper bound on the network lifetime, lifetimes of the individual nodes, idle time for each node, and total flow on each link are calculated. Even though these routing techniques maximize network lifetime, they do not account for MAC contention constraints. As a result, the routing solution may not be feasible. This might happen because these approaches often focus on the routing layer without accounting for the effects of underlying MAC layer. As a result, researchers have shifted the focus to cross-layer-aware routing design. In [13], a MAC aware, energy-efficient routing scheme is proposed for data aggregation in sensor network. This scheme deals with both objectives of maximizing the network lifetime and minimizing the total consumed energy.

WSNs with multiple sinks have also been studied; for e.g., in [7], two optimization problems are formulated with the objective of maximizing lifetime. In [10], the authors considered the commodity lifetime problem in MS-WSN. A stepwise algorithm is formulated to fairly share the network resources among various commodities, and to obtain the optimal routing solution. Even though these routing techniques maximize the lifetime of the network, they do not account for MAC contention constraints. As a result, the routing solution may not be feasible. In this work, we propose cross-layer aware data aggregation scheme that aims at maximizing the lifetime of MS-WSNs while accounting for MAC contention.

III. Network Topology and Assumptions

We model MS-WSN as a directed graph $G = (V, E)$, where V is a finite nonempty set of nodes and E is a set of wireless links (edges). The set V consists of a set of sensor nodes (N) and a set of multiple sink nodes (S) that collect information from N. Each edge $e \in E$ corresponds to an ordered pair of a distinct transmitter node and a receiver node (i, j) such that j is within $i's$ transmission range (i.e.; j is a neighbor of i) and i can transmit to j. Let N_i be the set of neighbors of node $i \in N$. An ordered pair of nodes (i, j) in E is said to form a link flow if i needs to transmit to j. Let k be any sink in S; then, a link flow from node $i \in N$ to $j \in N_i$ such that i has data to be destined to k is denoted by $(i, j)^k$. A flow $(i, j)^k$ is said to be active if i is currently transmitting to j, otherwise the flow is said to be inactive. We denote the set of link flows that are going to sink k as F^k; i.e., $\{(i, j)^k | i \in N; j \in N_i$ and i has data to be destined to $k \in S\}$, and $F = \bigcup_{k\in S} F^k$. We assume that each source node can generate and send data to one sink. Sinks, however, do not generate nor do it forward any data traffic. If a sensor node is not within a transmission range of the desired k, it relies on other sensor nodes to transmit its data. We assume that each $k \in S$ has an unlimited amount of energy. We also assume that G is connected (i.e., for each node i there is at least one path reaching to the desired sink). We further define the network lifetime as the time until the first node runs out of its energy resources, and we denote this lifetime by T.

IV. Data Aggregation

Assume that each source node i generates data traffic destined to sink $k \in S$ at a rate of R_i^k bits per second. Let x_{ij}^k denote the data rate (in bits per second) transmitted from node $i \in N$ to $j \in N_i$, and is going to be destined to sink k. The total data rate transmitted from node $i \in N$ to $j \in N_i$ is then equal to $\sum_{k\in S} x_{ij}^k$. Moreover, let $x = [x_{ij}^k]_{1\le i,j\le|N|,1\le k\le|S|}$ be the rate vector representing the rates of all the flows. Also, let $B_i(t)$ be the amount of energy available at sensor $i \in N$ at time t, and let c_{ij} denote the energy required to transmit one bit from node i to j. We assume that c_{ij} is constant for all nodes. Let W denote the maximum rate supported by the wireless medium. For each flow $(i, j)^k \in F^k$, let Ψ_{ij}^k denote the flow contention set defined as the set of all flows that cannot be active at the same time with $(i, j)^k$. Note that for every $(i, j) \in E, \Psi_{ij}^v = \Psi_{ij}^z$ for all $v, z \in S$. Our objective is to find a data rate solution that maximizes the network lifetime, T, while meeting the data rate requirements of all the flows. In the rest of this section, we first begin by presenting our routing constraints, and then describe our proposed routing approach.

A. Routing Constraints

The following set of constraints must be satisfied.

1) Flow Balance Constraints:

- At each node $i \in N$, the total outgoing rate must equal the sum of the incoming rates plus the rate of data generated by the node i; i.e.,

$$\sum_{j\in N_i} x_{ji}^k + R_i^k = \sum_{j\in N_i} x_{ij}^k; \qquad \forall k \in S,\ \forall i \in N \quad (1)$$

- At each sink $k \in S$, the total incoming rate must equal the total rate generated by all sensors whose data is destined to sink k; i.e.,

$$\sum_{i\in N_k} x_{ik}^k = \sum_{i\in N} R_i^k; \qquad \forall k \in S \quad (2)$$

- There is no traffic generated by any sink $k \in S$. That is,

$$x_{ij}^k = 0; \qquad \forall i \in S,\ \forall k \in S,\ \forall j \in N_i. \quad (3)$$

- All rates must be positive; i.e,

$$x_{ij}^k \ge 0; \qquad \forall i \in N,\ \forall j \in N_i,\ \forall k \in S. \quad (4)$$

2) Energy Consumption Constraints: Let t_0 be the initial time. The following must hold for each sensor node i

$$B_i(t_0) \ge T \sum_{j\in N_i} c_{ij} \sum_{k\in S} x_{ij}^k \quad (5)$$

3) Medium Contention Constraints: The rate vector x is feasible (i.e., satisfies the medium access constraints) if for each flow $(i, j)^k \in F^k$ the following MAC constraints hold [11].

$$\sum_{k\in S} x_{ij}^k \le W - \sum_{(p,q)^k \in \bigcup_{z\in S} \Psi_{ij}^z} x_{pq}^k \quad (6)$$

B. Routing Formulation

Let $f = 1/T$. The non-linear constraint (5) (in variables x and T) can then be equivalently written as the following linear constraints (in variables x and f)

$$f \ge \frac{1}{B_i(t_0)} \times \sum_{j\in N_i} c_{ij} \sum_{k\in S} x_{ij}^k \quad (7)$$

Note that maximizing T is equivalent to minimizing f. The routing problem can then be formulated as:

Minimize f

Subject to:

Flow Balance Constraints: (1)-(4).

Energy Consumption Constraints: (7).

Medium Contention Constraints: (6).

V. Performance Evaluation

We now use MATLAB to evaluate the effectiveness of the proposed data aggregation scheme. We first investigate the effect of MAC contention constraints on the physical feasibility of the routing solution, and then analyze the network lifetime.

A. *Solution Feasibility Evaluation*

MAC constraints prevent the nodes that are in the same communication range from transmitting at the same time. As a result, the rate solutions obtained are ensured to be feasible. However, without considering these constraints, the rate solution may not be feasible. In this subsection, we illustrate the importance of considering the coupling effects between MAC and network layers by studying the effect of not including MAC contention constraints on the physical feasibility of the routing solution. For this, we simulate MS-WSNs using the proposed routing scheme, but without including MAC contention constraints to the formulation. We then study the feasibility of the solutions based on whether they meet the MAC contention constraints. If the solution obtained by solving the routing algorithm for a simulated graph meets MAC contention constraints (Equation 6) as well as the other constraints, then the graph is said to be feasible.

1) Simulation setup and method : We generate one hundred random MS-WSNs, each of which consists of a set of sensor nodes (N) and multiple sink nodes (S). The sensor and sink nodes are randomly distributed in a $100m \times 100m$ square field. Each source node generates and sends data traffic with a rate requirement of $R_i^k = 0.01$ to a randomly selected sink k among available sinks. Without loss of generality, we assume that $W = 1$. All simulated MS-WSNs graphs are connected.

2) Effect of number of sinks: In this experiment, we investigate the performance of our routing scheme on graph feasibility when varying the number of sink nodes. Again, we simulate our routing scheme but without including MAC contention constraints in order to study the physical feasibility of the rate solution. Fig. 1 shows the number of feasible graphs out of 100 simulated graphs versus the number of sinks. It is clear from the figure that as the number of sinks increases, the percentage of feasible graphs increases. When the number of sinks is low (e.g., one), all the nodes tend to forward their traffic to the same sink(s), thereby increasing the contention in the sinks' neighborhoods. This results in lesser feasible graphs. On the other hand, the higher the number of sinks is, the more balanced the contention across the network is.

3) Effect of average node degree: Here, we illustrate the effect of not including MAC contention constraints on the physical feasibility of the routing solutions while varying the average node degree by varying the number of sensor nodes from 30 to 70. Note that as the number of sensor nodes increases, the average node degree increases. In this experiment, we consider two sink nodes. Fig. 2 shows the number of feasible graphs out of 100 simulated graphs versus the number of sensor nodes. First, the figure shows that as the average node degree increases, the percentage of feasible graphs increases regardless of the number of sinks. Second, it also shows that, as expected, the higher the number of sinks, the greater the percentage of feasible graphs. When the average node degree is high, nodes have more route options to route through because they have more neighbors, leading to higher percentages of feasible graphs. On the other hand, when the average node degree is low, nodes have fewer neighbors and hence are likely to route their traffic through the same paths, thus increasing the contention especially around the sinks which results in less feasibility.

4) Effect of network load: In the this experiment, we vary the network load by varying the number of source nodes that generate and send traffic from 5 to 40. Fig. 3 shows the number of feasible graphs out of 100 simulated graphs versus the number of source nodes. The figure shows that when the network load increases, graph feasibility decreases. This is because when the network load (the number of source nodes that generate and

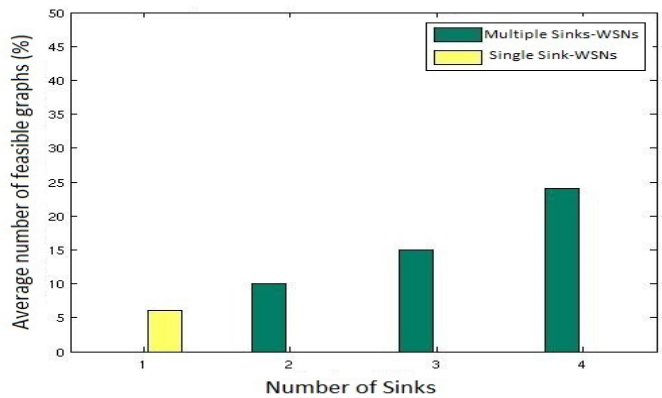

Fig. 1. Effect of number of sinks on graph feasibility. Number of sensor nodes = 40, Transmission range = 35m, Number of source nodes = 40.

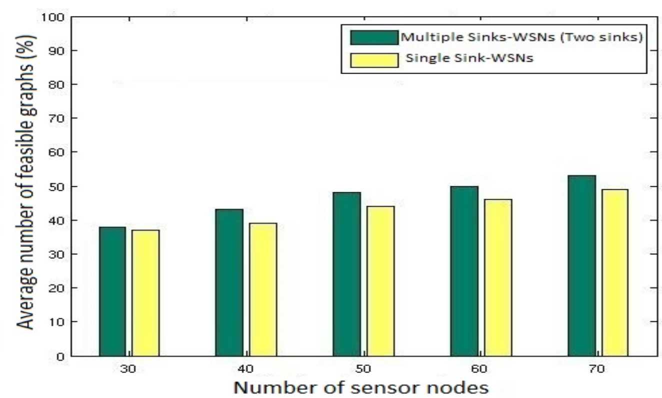

Fig. 2. Effect of number of average node degree on graph feasibility. Number of sensor nodes = 40, Transmission range = 35m, Number of source nodes = 30.

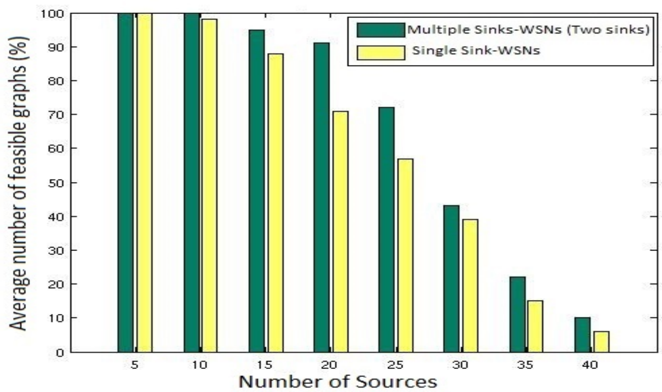

Fig. 3. Effect of number of network load on graph feasibility. Number of sensor nodes = 40, Transmission range = 35m.

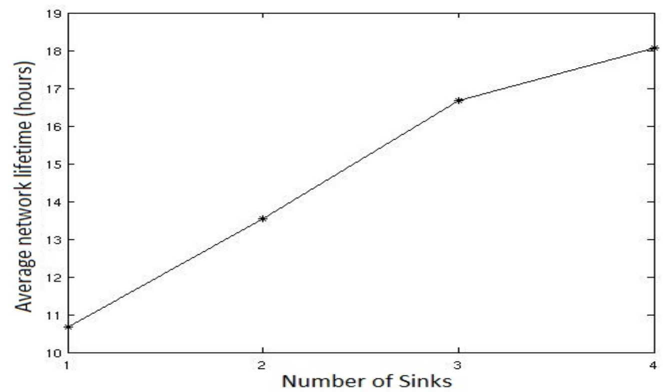

Fig. 5. Effect of the number of sinks on network lifetime. Number of sensor nodes = 40, Transmission range = 35, Number of source nodes = 40.

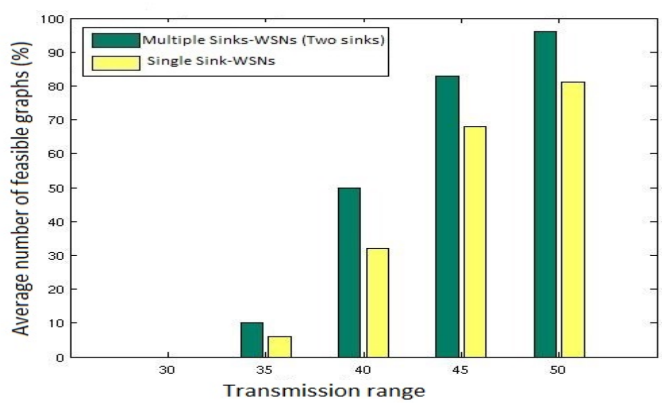

Fig. 4. Effect of transmission range on graph feasibility. Number of sensor nodes = 40, Number of source nodes = 40.

forward traffic) is high, the level of interference is also high, resulting in more physical infeasibility.

5) Effect of transmission range: Fig. 4 shows the number of feasible graphs out of 100 simulated graphs under various transmission ranges: $30, 35, 40$, and 45m. First, observe that as the transmission range increases, the feasibility of rate solutions increases. This happens because as the transmission range increases, the average hop length decreases, and since c_{ij}^k is fixed, nodes tend to route through the least number of hops. Therefore, when the transmission range is high, the hop length is low; i.e., nodes are more likely to route through fewer numbers of hops, resulting in generating less contention which explains the high percentage of feasible graphs.

B. Network Lifetime Evaluation

We now evaluate the lifetime performance of our routing approach. Unlike the previous subsection, the MAC contention constraints are now considered.

1) Simulation setup and method: To evaluate the network lifetime, random WSNs are generated and simulated. Each network graph is simulated many times (until the results converge), and results are averaged over these simulation runs. In each simulation run, each source node i is assumed to generate fixed data traffic with a rate requirement of $R_i^k = 0.0005$ bits per second and send it to sink k. We again assume that $W = 1$ bit per second, and that $B_i(t_0) = 1$ Joule for each sensor node i. All simulated MS-WSNs graphs are connected. IEEE802.11 MAC protocol is utilized for our simulation, which dictates that if node i is in communication with node j, then all nodes within the same communication range of i or j cannot communicate.

2) Effect of number of sinks: Fig. 5 shows the average network lifetime when varying the number of sink nodes. The figure shows that, as expected, as the number of sinks increases, the lifetime of the network increases. This is because as the number of sink nodes increases, the average per-sink workload decreases. For e.g., when there is one sink only, the nodes around the sink have to forward all messages coming from all sensors, forcing their energy resources to deplete quickly, which in turn decreases the network lifetime. However, when more sinks are deployed and spread all over the network area, the traffic load is balanced among them, reducing then the average per-sink workload. This results in an increase in the network lifetime.

3) Effect of average node degree: Here, the average node degree is varied by varying the number of sensor nodes. Fig. 6 shows the network lifetime when varying the number of sensor nodes from 30 to 70. Observe that, regardless of the number of sinks, the network lifetime increases with the average node degree (i.e., with the number of sensor nodes). This is because the higher the average node degree, the higher the path alternatives to route through, due to the increased number of neighbors. But when the average node degree is low, the number of alternative paths is limited, resulting in early node failures, and thus, in shorter network lifetimes.

4) Effect of network load: Fig. 7 shows the network lifetime when varying the numbers of source nodes from 5 to 40. As expected, observe that the lifetime is longer when the number of sinks is higher. It also decreases when the network load increases because higher load means higher data traffic, leading to faster energy depletion and thus shorter network lifetimes.

5) Effect of transmission range: Fig. 8 shows the network lifetime when varying the transmission ranges from 30 to 50 meters. Observe that the network lifetime increases with the transmission range. This is because when the transmission range

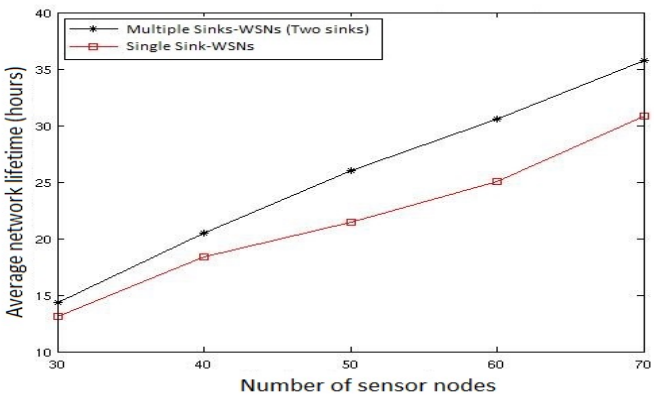

Fig. 6. Effect of the average node degree on network lifetime. Transmission range = 35, Number of source nodes = 30.

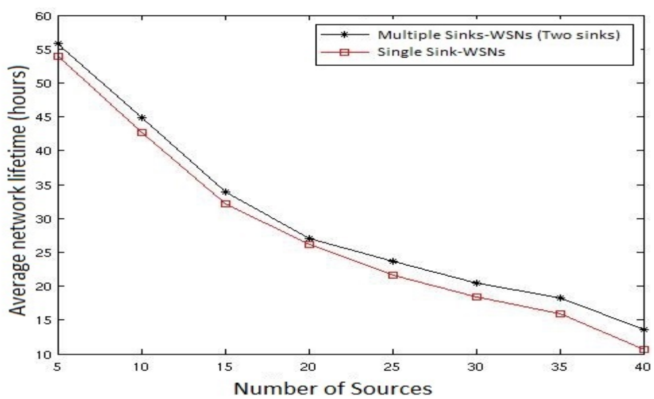

Fig. 7. Effect of the network load on network lifetime. Number of sensor nodes = 40, Transmission range = 35.

is large, the number of neighbors is, on average, also large, creating more route alternatives. But when the transmission range is low, nodes have fewer number of neighbors and hence they tend to route through the same nodes to reach their sinks. This leads to fast energy node depletion and consequently to shorter network lifetime.

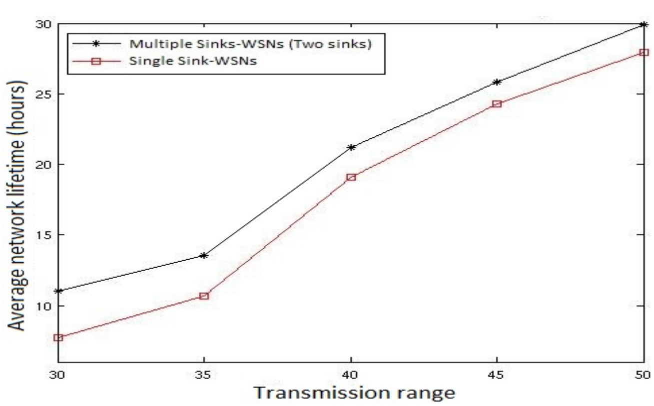

Fig. 8. Effect of the transmission range on network lifetime. Number of sensor nodes = 40, Number of source nodes = 40.

VI. Conclusion

We propose a cross-layer data-aggregation technique for rate constrained traffic in MS-WSNs that is both energy aware and medium contention aware. We demonstrate the importance of coupling between network and medium access layer by studying the effect of not including the medium access constraints on the physical feasibility of the routing solution. We also study the impact of several network parameters on the network lifetime.

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