AN ABSTRACT OF THE THESIS OF

Arwa Zakaria Hamid for the degree of Master of Science in Computer Science
presented on June 4, 2013.

Title: Cross-Layer Aware Routing Approach for Lifetime Maximization in Wireless Sensor Networks with Multiple Sinks

Abstract approved: ______________________________

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In wireless sensor networks (WSNs) nodes are battery powered. Therefore, the available energy resources of sensor nodes should be managed efficiently in order to increase the network lifetime. As a result, researchers have proposed routing schemes in order to maximize network lifetime. Even though these schemes increase the network lifetime, the majority of these schemes do not account for MAC contention constraints associated with the shared medium. Consequently, the rates of the flows obtained by solving the routing schemes might not be feasible in practice. Recently, cross-layer aware routing approaches were proposed for WSNs that increase the network lifetime and insure the feasibility of the routing solutions. However, these approaches are proposed for WSNs with single sink. In this paper, we extend this problem into a multi-sink case. To maximize the network lifetime and to ensure the feasibility of the routing solution, we propose a cross layer aware routing approach that (i) accounts for MAC and network

layers, (ii) maximizes the network lifetime, and (iii) is applicable for WSNs with multiple sinks. One of the sufficient conditions, referred to as rate-based constraints is incorporated into our routing formulation in order to guarantee medium access feasibility of the routing solutions. Simulation results show that our routing approach for networks with multiple sinks achieves longer lifetime and better solution feasibility compared to the approach proposed for networks with single sink.

Cross-Layer Aware Routing Approach for Lifetime Maximization in Wireless Sensor Networks with Multiple Sinks

by

Arwa Zakaria Hamid

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented June 4, 2013
Commencement June 2013

Master of Science thesis of Arwa Zakaria Hamid presented on June 4, 2013.

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Arwa Zakaria Hamid, Author

ACKNOWLEDGEMENTS

All praise and glory to Allah the almighty who alone made this thesis to be accomplished. I am honored and privileged to glorify his name in the sincerest way through this accomplishment and ask him to accept my effort. Peace and mercy be upon his prophet Mohammad.

I would like to express my deepest and sincere gratitude to my advisor Dr. Bechir Hamdaoui for his guidance, advices, constant help, and support. I also would like to thank Samina Ehsan for her great help, and contribution during my research work. I also thank my thesis committee members Dr. Eduardo Cotilla-Sanchez, Dr. Bella Bose, and Dr. Michael Olsen for their invaluable cooperation.

I owe my deepest gratitude to my husband, my soul mate, Hatem Abuelizz, for his patience. I would not have been completed my studies without his encouragement and support, after Allah's help. I also would like to thank my little pie, my son Adi for his patience. I really admit that my studies took me away from him, but after all, I dedicate my work to him. I also would like to express my sincere gratefulness to my parents, Zakaria Hamid and Seham Sulaiman for their prayers and words of encouragement. I also thanks my siblings, Ahmed, Abdulrahman, Anas, Ragad, Sozan, Nissreen and their families for their love and nice wishes. Special thanks to my parents in low, Ahmad Abuelizz, and Ablah Albalbeesi, and my brothers and sister in lows, Shahd, Amer, and Hazem for their prayers and love. I ask Allah to bless them. I also thanks all my friends, research and collaborative groupmates for their invaluable help throughout my studies.

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I dedicate this work to my husband, my son, my parents, my siblings, my nieces, my parents in law, and my friends, who offered me unconditional love, prayers, and support.

Chapter 1: INTRODUCTION

1.1 Wireless Sensor Networks

During the last decade, Wireless Sensor Networks (WSNs) have been the focus of many researchers due to the feasibility to use numerous small and low-cost sensor nodes. A typical wireless sensor network consists of a large number of battery-powered sensor nodes that are capable of sensing, processing, and gathering data from surroundings environments and transmitting them to a data collector called a sink (or base station). An example of WSN is shown in Figure 1.1. The sensor nodes can be randomly deployed in an area of interest, and each node can be equipped with any kind of sensor such as temperature, humidity, vehicular movement, lightning condition, or pressure [1]. Due to the availability of low cost, small size sensor nodes, and the ability of wireless communication between nodes, there is a wide range of applications in WSNs such as monitoring environments, military, industry, health care, security, and home applications [1,2].

1.2 Issues and Challenges in WSNs

WSNs have their unique characteristics which create new challenges when designing routing protocols and techniques for such networks. In this section, we discuss three different challenges when designing routing protocols for WSNs. These challenges are:

network lifetime, limitation of single sink deployment in such networks, and solution feasibility of routing schemes.

1.2.1 Network Lifetime

Sensor nodes are very limited in computational capabilities, storage capacity, and transmission power. Generally, sensor nodes have a limited lifetime because batteries can be irreplaceable and sensors are often located in hard or impossible to reach locations such as underground, underwater, on mountains, or in the forest. Therefore, battery resources should be managed and handled efficiently in order to save energy and maximize their lifetime to prolong network lifetime. This can be done by designing energy efficient routing techniques to prolong the network lifetime.

Network lifetime can be defined based on what is suitable for the context of the author's work. Therefore, the following is an overview of the most common definitions of network lifetime [3]:

1. Network lifetime based on the number of live nodes, (excluding the sink node). Based on the above general definition, network lifetime can be defined as one of the following:

    - The time at which the first node runs out of energy. That means all nodes must be alive.
    - Most of the nodes must be alive.
    - All cluster heads must be alive.

2. Based on the coverage:

   This definition addresses the coverage of the network where for a network to be alive, it must entirely cover the area of interest.

3. Based on connectivity:

   This approach defines lifetime in term of live links between nodes and the sink node. Usually there is a certain threshold where the network is considered alive until certain number of connections are dead.

4. Based on application:

   This definition associates the lifetime with the application requirements. A network is considered alive as long as it satisfies the application requirements.

1.2.2 Limitation of Single Sink Deployment in WSNs

A typical WSN is composed of a sink node and a number of sensor nodes. Each sensor node has a small sensing coverage and a small communication range (because increasing the sensing coverage and communication range would consume more battery power). Therefore, sensor nodes send the sensed events to the sink node through multi-hop wireless links. The problem of ”sink neighborhood” is where sensor nodes that are placed around the sink node consume their energy and deplete faster than other nodes. This is because all the data traffic must be forwarded through them to reach the sink node. As a consequence,the sink node becomes unable to receive any further packets.

In some applications, such as environmental monitoring or surveillance, scalability is important. Thus, in such large scale networks, it would be inefficient in terms of energy consumption to gather all the sensed data in one sink [4]. In addition, as the network size increases, the contention around the sink increases which in turn may result in physical infeasibility of the routing solutions.

Also, in some applications, such as fire monitoring and military surveillance, reliability is important, where copies of data have to be sent to more than one sink to insure minimum packet loss [5]. In WSNs with single sink, the invalidation of the sink node (for any reason) will cause a breakdown of the whole WSN [6].

To solve the above problems, multiple sink nodes can be deployed in WSNs. Multiple sink deployment in WSNs decreases the energy consumption of sensor nodes, increases the network lifetime, decreases the contention around the sinks, and insures the reliability of data.
Sample MS-WSN (with two sinks) versus SS-WSN are illustrated in figure 1.2. The figure shows that, in the MS-WSN example, 50% of the source nodes (SN) generate and send data traffic to the first sink, and the other 50% of SN send data traffic to the second sink node. On the other hand, in SS-WSN all SN generate and send data traffic to the same sink node.

1.2.3 Solution Feasibility of Routing Techniques

We have mentioned earlier in this chapter that since nodes are battery operated, efficient use of their available energy resources is important. As a result, researchers have been designing routing schemes for lifetime maximization in WSNs with single sink (SS-

WSNs) [7–10], and in WSNs with multiple sinks (MS-WSNs) [4, 11–13]. 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 constraints 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. By understanding the above issue, designing cross-layer aware routing schemes that are energy efficient is important. As a result, during the last few years, researchers have shifted their attention toward cross-layer design for WSNs [14, 15]. For further details, please refer to Chapter 2. Although there are many cross-layer aware routing techniques that are energy efficient, the majority of them have designed these techniques over SS-WSNs. We have mentioned earlier in this chapter the importance of deploying multiple sinks in such large scale wireless sensor networks. Therefore in this work,we propose a routing approach for WSNs with multiple sinks that first is cross layer aware by accounting for radio, MAC contention,and network constraints, and second is energy efficient by maximizing the network lifetime.

1.3 Contributions and Thesis Organization

Our primary contributions of this research are as follows. We propose MAC-aware routing scheme in WSNs with multiple sinks to maximize the network lifetime. One of the three sufficient conditions proposed in [16], (referred to as rate-based) is used as a base for ensuring feasibility of the obtained routing solutions in regard to the medium access contention constraints. Since rate-based condition is linear, we formulate our routing problem using linear programming, where the objective function is to maximize the network lifetime for a provided data rate. We also study the performance of our routing approach in MS-WSNs (in terms of solution feasibility and network lifetime) by comparing it with a routing approach designed for SS-WSNs.

The rest of this thesis is organized as follows. Chapter 2 presents some of the literature work related to our research. In Chapter 3, we describe our network model and assumptions. Chapter 4 discusses the proposed routing technique for WSNs with multiple sinks. We then, in Chapter 5, study the performance of our routing approach in MS-WSNs. Finally, we conclude the thesis in Chapter 6.

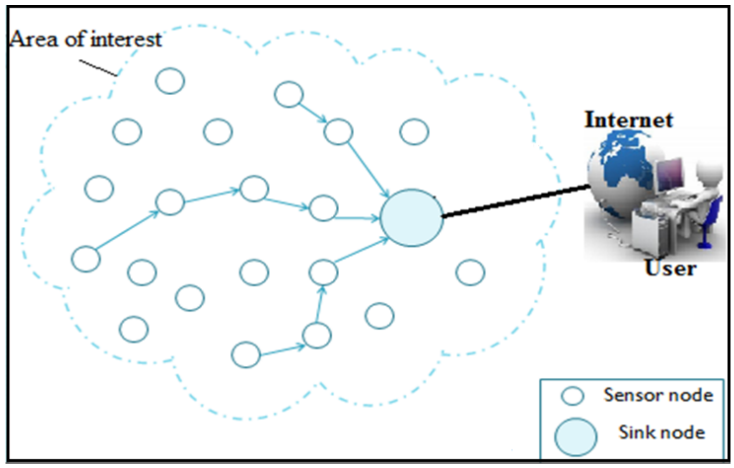

Figure 1.1: Sample Wireless Sensor Network (WSN).

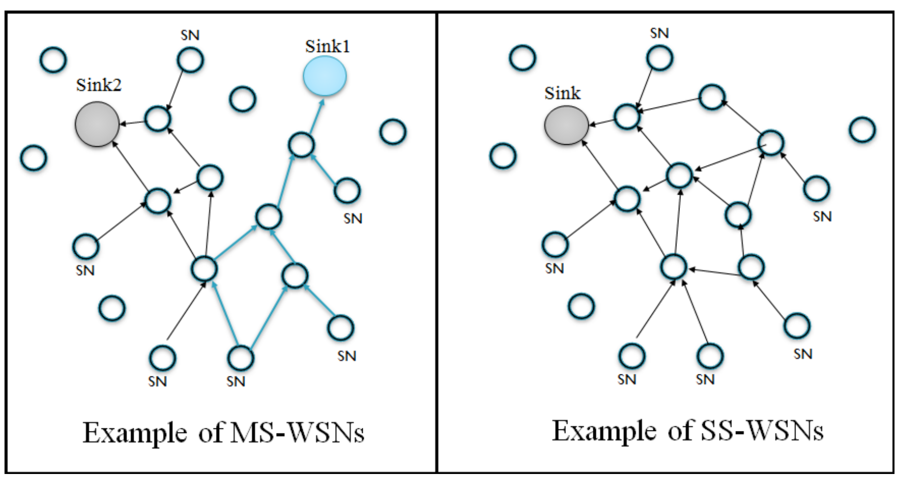

Figure 1.2: Sample WSN with multiple sinks (two sinks) versus WSN with single sink node

Chapter 2: RELATED WORK

In WSNs, since energy conservation is important for increasing the network lifetime, a significant research effort has been directed towards routing techniques that are energy aware. In Chapter 1, we discussed the effect of deploying single sink versus multiple sinks in WSNs. In this Chapter, we present some of the literature reported for SS-WSNs and then we present the same for MS-WSNs.

Numerous routing techniques have been proposed for SS-WSNs with an emphasis on energy consumption [7–10,17]. For example, in [8] 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, upper bound on the network lifetime, lifetimes of the individual nodes, idle time for each node, and total flow on each link is calculated. In [7], a distributed routing technique that is energy efficient is proposed for WSNs. The maximum lifetime routing problem is formulated as linear programming based on flow conservation constraints while balancing energy consumption in proportion to the nodes remaining energy. 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. This might happen because most of the approaches proposed in the literature focus on the routing layer without accounting for the effects of underlying MAC layer. To tackle this problem, cross layer design involving both network layer and MAC layer should be considered. As a result, researchers have recently become motivated to shift the focus to cross-layer design in their routing schemes. In [14], a MAC aware routing scheme that is energy efficient 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. In [15], Three MAC-aware schemes are proposed for routing rate-constrained traffic in WSNs that maximize network lifetime. Three sufficient conditions (referred to as rate-based, degree-based, and mixed-based) are used as basis for ensuring feasibility of the obtained routing solutions in regard to the medium access contention constraints. To illustrate, in the first scheme (called LP-1) the rate-based condition constraints are incorporated into the routing formulation. In the second scheme (LP-2), the degree-based condition constraints are used in the routing formulation. And in the third scheme (IP), the mixed-based condition constraints are incorporated into the formulation.

It is worth noting that the algorithms in [14, 15] are proposed specifically for SS-WSNs. Since there are many problems in traditional single sink sensor networks, as discussed in Chapter 1, MS-WSNs have recently received increasing attention by many researchers in [4, 11–13, 18, 19]. For example, in [11], the upper and lower bounds are derived, and two optimization problems are formulated for lifetime maximization in MS-WSNs. In [4],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. Therefore, cross layer design involving network layer and MAC layer should be considered for wireless sensor networks with multiple sinks. In this work, we propose cross-layer aware routing scheme for lifetime maximization in MS-WSNs. This routing scheme account for network and MAC layers.

Chapter 3: 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 many sensor nodes (N) and 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 a 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 sink k does not generate and does not forward data traffic. Each source node generates and sends data traffic to a particular sink. While all sensor nodes forward data traffic to $k \in S$, source nodes are the only nodes that generate data traffic. If any of the sensor nodes are not within a transmission range of the desired k, it relies on other sensor nodes to transmit the data to this particular k. We assume that each $k \in S$ has unlimited amount of energy, since they are connected to an accessible power-supplied, and external information infrastructure. 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 as T.

Chapter 4: ROUTING TECHNIQUE

Consider a MS-WSN defined in Chapter3, where 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 (number of 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 denoted by $\sum_{k \in S} x_{ij}^k$. Moreover, let $X = [x_{ij}^k]_1 \leq i, j \leq |N|, 1 \leq k \leq |S|$, be the rate vector representing the rates of all the flows. Also, let $B_i(t)$ be the energy resources available at sensor node $i \in N$ for network communication at a given time t. The energy required to transmit a bit from node i to j is denoted by c_{ij}, (the cost of transmitting one bit over a wireless link). We assume that c_{ij} is constant for all nodes. Let W denote the maximum rate supported by the wireless medium (capacity of the wireless medium). For each flow $(i, j)^k \in F^k$, letΨ_{ij}^k denote to the flow contention set (the set of all flows that cannot be active at the same time $(i, j)^k$ is active). Note that for every $(i, j) \in E, \Psi_{ij}^v = \Psi_{ij}^z$ for all $v, z \in S$. Given the required rate vector $R = [R_i^k]_1 \leq i \leq |N|, 1 \leq k \leq |S|$, we aim at finding a routing solution that maximizes the network lifetime, T, while meeting the data rate requirements of all the flows. In this section, we describe our proposed routing approach which ensures that the obtained routing solutions indeed meet the flows' data rate requirements. First, we present the routing constraints, and second, we present the routing formulation.

4.1 Routing Constraints

Given the required rate vector $R = [R_i^k]_1 \leq i \leq |N|, 1 \leq k \leq |S|,$, the following set of constraints must be satisfied.

4.1.1 Flow Balance Constraints:

1. At each node $i \in N$, the total outgoing rate must equal to the sum of the incoming rate and the data rate generated by the node $i \in N$, for every sink k.

$$\sum_{j \in N_i} x_{ji}^k + R_i^k = \sum_{j \in N_i} x_{ij}^k; \qquad \forall k \in S,\ \forall i \in N \tag{4.1}$$

2. Let N_k be the sensor nodes that are neighbors for sink k. Then, For each sink $k \in S$, the total incoming data rate must equal the total data rate generated by all Sensor nodes that are going to sink k,

$$\sum_{i \in N_k} x_{ik}^k = \sum_{i \in N} R_i^k; \qquad \forall k \in S \tag{4.2}$$

3. There is no traffic generated by any sink $k \in S$.

$$x_{ij}^k = 0; \qquad \forall i \in S,\ \forall k \in S,\ \forall j \in N_i. \tag{4.3}$$

4. All rates in F must be positive, for $(i,j)^k$, for all $k \in S$.

$$x_{ij}^k \geq 0; \qquad \forall i \in N,\ \forall j \in N_i,\ \forall k \in S. \tag{4.4}$$

4.1.2 Energy Consumption Constraints:

We have mentioned in Chapter 3 that sinks are assumed to have infinite amount of energy. However, sensor nodes have limited power. Thus, let t_0 be the initial time. Then, if each sensor node i has $B_i(t_0)$ amount of energy at the initial time t_0, the remaining energy at future time t_0+T will be greater than or equal to 0. Therefore, for each sensor node i,

$$B_i(t_0) \geq T \sum_{j \in N_i} c_{ij} \sum_{k \in S} x_{ij}^k \tag{4.5}$$

4.1.3 Medium Contention Constraints:

In this paper, we incorporate one of the sufficient conditions (referred to as rate based condition) into the routing formulation to guarantee medium access feasibility of the routing solution. As stated before, the routing solutions may not be feasible in practice without including medium contention constraints in the routing formulation. The rate based constraints [16] are presented as follows:

The rate vector of X is feasible (i.e., it satisfies the medium access constraints) if for each flow $(i,j)^k \in F^k$ the following medium contention constraints hold.

$$\sum_{k \in S} x_{ij}^k \leq W - \sum_{(p,q)^k \in \bigcup\limits_{z \in S} \Psi_{ij}^z} x_{pq}^k \tag{4.6}$$

Note that if the rate vector X satisfies these constraints, then, that means there exists a time schedule in which the rates of all flows are satisfied. In the following section, we formulate the routing problem using the rate based contention constraints.

4.2 Routing Formulation

The routing problem is to determine the rate vector X that maximizes the network lifetime subject to (4.1) - (4.6), Routing constraint (4.5) is not linear. However, it can be converted to a linear program by introducing a new variable ,f, which is equivalent to $1/T$. Then, we rewrite the constraint (4.5) as the following:

$$f \geq \frac{1}{B_i(t_0)} \times \sum_{j \in N_i} c_{ij} \sum_{k \in S} x_{ij}^k \tag{4.7}$$

The objective of maximizing the lifetime T can be achieved by minimizing f due to the inverse relationship. The routing problem is formulated as follows:

Minimize f

Subject to:

Flow Balance Constraints: Eq. (1.4)-(4.4).

Energy Consumption Constraints: Eq. (4.7).

Medium Contention Constraints: Eq. (4.6).

In the following chapter, we solve the linear programming problem for several conditions.

Chapter 5: PERFORMANCE EVALUATION

In this chapter, the performance of our proposed routing scheme is evaluated and analyzed. MATLAB is used as a tool to solve the formulated routing optimization problem. In this evaluation, we consider two simulation studies:

- solution feasibility: we investigate the effect of MAC contention constraints on the physical feasibility of the routing solution obtained under the routing scheme.
- network lifetime: we analyze the network lifetime performance of the proposed scheme.

Moreover, in each of the simulation studies, we compare our routing approach proposed for MS-WSNs to an existing routing approach called (LP-1) that is proposed for SS-WSNs in [15], and discussed in Chapter 2.

5.1 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 section, we illustrate the significance of the coupling between MAC and network layers solutions by studying the effect of not including MAC contention constraints on the physical feasibility of the routing solution. To demonstrate this effect, 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 MAC contention constraints. If the solution obtained by solving the routing algorithm for a simulated graph meets MAC contention constraints (Equation 4.6) as well as the other constraints then the graph is said to be feasible.

In the following subsections, we describe the simulation setup and then we study the graph feasibility considering the effect of the following parameters: number of sinks deployed in such networks, network load, average node degree, and transmission range.

5.1.1 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 nodes are randomly and uniformly distributed in a $100m \times 100m$ square field. The sinks are randomly placed. Each source node generates and sends data traffic with a rate requirement of $R_i^k = 0.01$ to sink k. For example, when two sink nodes are considered in the network, randomly 50% of the source nodes generate and send data traffic to the first sink, and the other 50% generate and send traffic to to the second sink. For more illustration, if four sink nodes are deployed in a network, randomly, 25% of source nodes generate data traffic to the first sink, another random 25% of source nodes generate and send traffic to the second sink, the third and the fourth 25% of source nodes likewise generate and send traffic to the third and fourth sinks. Because of the randomness of this setup, for each network graph generated, we have done 50 simulation runs to ensure the convergence of the results. Without loss of generality, we assume that $W = 1$, where W is the maximum data rate of the wireless medium. All simulated MS-WSNs graphs are connected, which means that each sensor node can communicate with sink nodes directly or through a set of intermediate relay nodes. For simulating LP-1 on SS-WSNs, one sink is randomly employed. All source nodes generate and send data traffic to the sink with fixed rate requirement of $R_i^1 = 0.01$. Other simulation setups are the same as mentioned in case of MS-WSNs.

5.1.2 Effect of Number of Sinks on Graph Feasibility

In the first experiment, we investigate the performance of our routing scheme on graph feasibility when varying the number of sink nodes employed. Again, we simulate our routing scheme on MS-WSNs but without including MAC contention constraints, in order to study the physical feasibility of the rate solution. We also compare our routing scheme in MS-WSNs to LP-1 in SS-WSNs. The number of sensor nodes is set to 40. The transmission range is set to 35 meters. The network load is 40 source nodes. The number of sink nodes is varied from one sink to four sink nodes. Figure 5.1 shows the number of feasible graphs out of 100 simulated graphs versus the number of sinks.

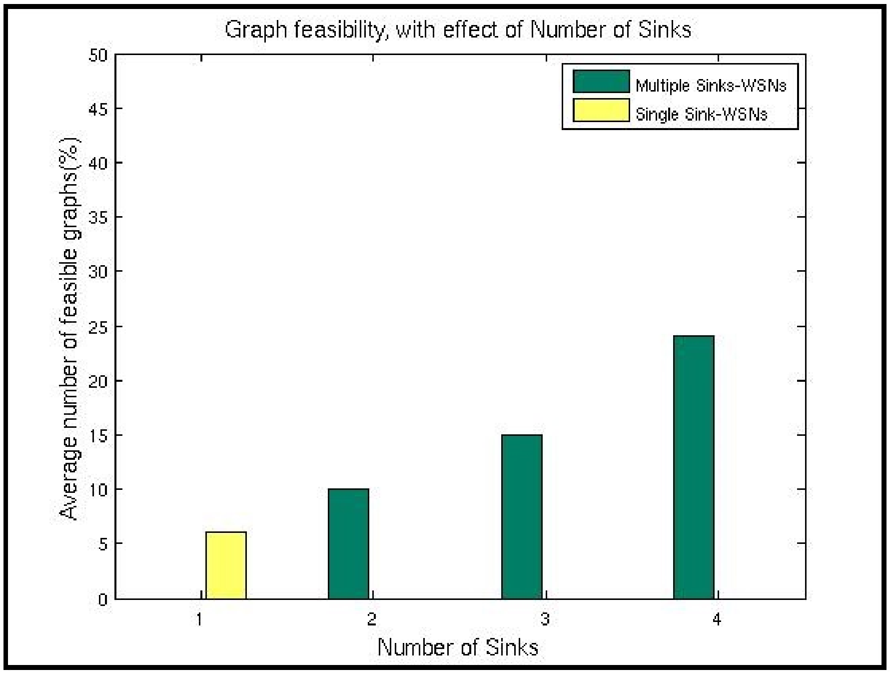

Figure 5.1: Graph feasibility, with effect of number of sinks: Number of sensor nodes $= 40$, Network load $= 40$ source nodes, Transmission range $= 35$.

5.1.2.1 Result Analysis

It is clear from graph 5.1 that our routing scheme simulated over MS-WSNs is more likely to result in more feasible graphs than LP-1 simulated over SS-WSNs. As the graph shows, as the number of sinks increases, the physical feasibility of the rate solution increases. We analyze the results as follows:

- First case, deploying one sink node for WSNs: All the nodes forward their traffic through their sink neighbors. This, in turn, increases the contention of the neighborhood around the sink.

- Second case, deploying two sink nodes for WSNs: Randomly, 50% of nodes forward their traffic to the first sink, and the other 50% of nodes forward their traffic to the second sink. This, in turn, reduces the load and then the contention around each sink.

- Third case, deploying three sink nodes for WSNs: Randomly, the first third of the nodes forward traffic to the first sink, the second third of nodes forward their traffic to the second sink, and the last third forward traffic to the third sink. In this case, more balanced contention is achieved around the sinks because the load is distributed among the three sink nodes.

- Fourth case, deploying four sink nodes for WSNs: Randomly, 25% of source nodes generate data traffic to the first sink, another random 25% of source nodes generate and send traffic to the second sink, a third 25% of source nodes generate and send traffic to the third sink, and the last 25% generate and send traffic to the fourth sink. This, in turn, reduces the workload around sink nodes and achieves best balanced contention around the four sink nodes.

In summary, our routing approach for MS-WSNs achieves a greater number of graph feasibility of rate solutions than the routing approach LP-1 that is simulated over SS-WSNs.

5.1.3 Effect of Average Node Degree on Graph Feasibility

In the second experiment, we illustrate the effect of not including MAC contention constraints on the physical feasibility of the routing solutions with the impact of the average node degree. We also compare between our routing approach over MS-WSNs with LP-1 over SS-WSNs. The transmission range is fixed and equal to 35 m. Also, the network load is fixed and equal to 30 source nodes. Here, we vary 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 as MS in WSNs. Figure 5.2 shows the number of feasible graphs out of 100 simulated graphs versus various number of sensor nodes.

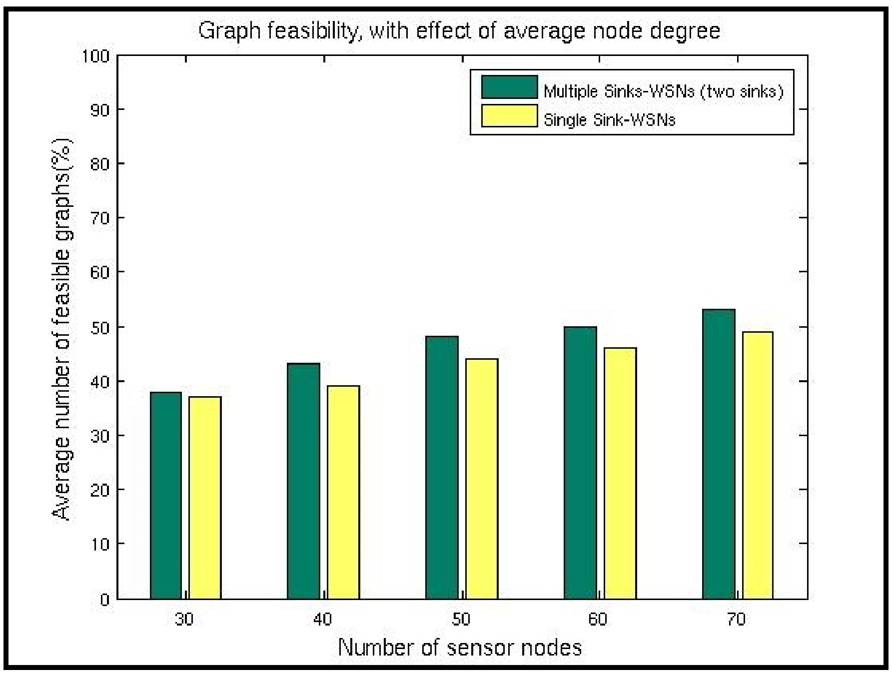

Figure 5.2: Graph feasibility, with effect of average node degree: Network load = 30 source nodes, Transmission range = 35.

5.1.3.1 Result Analysis

Under the effect of average node degree, our routing approach achieves a slightly greater number of feasible graphs than LP-1. Figure 5.2 shows that regardless of whether the routing approach is applied for single sink or multiple sink WSNs, as the average node degree increases, the percentage of feasible graphs increases. To illustrate, when the average node degree is high, nodes can route through many paths because they have more neighbors; thus, the percentage of feasible graphs is high. On the other hand, when the average node degree is low, nodes have fewer neighbors; thus, they are likely to route through the same paths. This, in turn, increases the contention (especially around the sinks, because nodes forward their traffic through sink neighbors) resulting in less feasibility of rate solutions.

5.1.4 Effect of Network Load on Graph Feasibility

In the third experiment, we also study the effect of network load on the graph feasibility. Also, we compare between our routing approach with LP-1. The transmission range is fixed and equal to 35. Also, the number of sensor nodes (or average node degree) is fixed and equal to 40. To vary the network load, the number of source nodes that generate and send traffic to the sink nodes is varied from 5 to 40. In this experiment, we also consider two sink nodes as MS in WSNs. Figure 5.3 shows the number of feasible graphs out of 100 simulated graphs versus the number of source nodes.

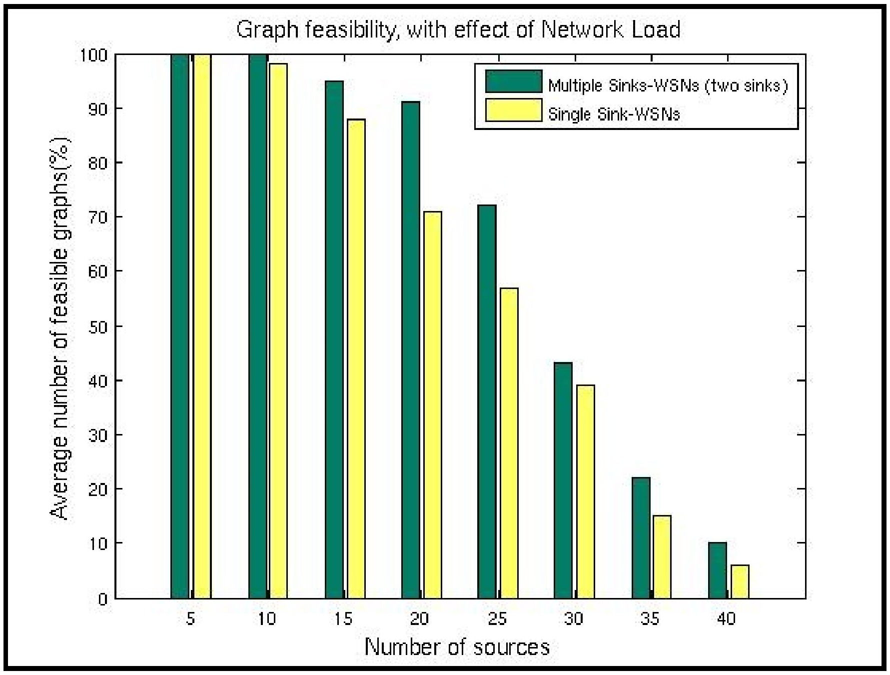

Figure 5.3: Graph feasibility, with effect of network load: Number of sensor nodes $= 40$, Transmission range $= 35$.

5.1.4.1 Result Analysis

Figure 5.3 shows that for both MS-WSNs and SS-WSNs, when the network load increases, feasibility of rate solutions decreases. This is because when the network load is high, the number of source nodes that need to generate and forward their traffic is high, which, in turn, increases the level of interference resulting in more physical infeasibility of the rate solutions. However, when the network load is low, the number of source nodes is low; thus, traffic forwarded by nodes is low, which results in less contention. In this case, graphs with low network load result in more feasibility of the routing solutions. Also the figure shows that our routing approach for MS-WSNs achieves better number of feasible graphs comparing it to LP-1 simulated over SS-WSNs.

5.1.5 Effect of Transmission Range on Graph Feasibility

In the fourth experiment, we study the effect of transmission range on the graph feasibility, and compare our routing approach to LP-1. We simulate the following transmission ranges: $30, 35, 40$, and $45m$. We fix the number of sensor nodes which is equal to 40. We also fix the network load which is equal to 40 source nodes. We also consider two sink nodes for the MS-WSNs. Figure 5.4 shows the number of feasible graphs out of 100 simulated graphs versus the transmission ranges considered.

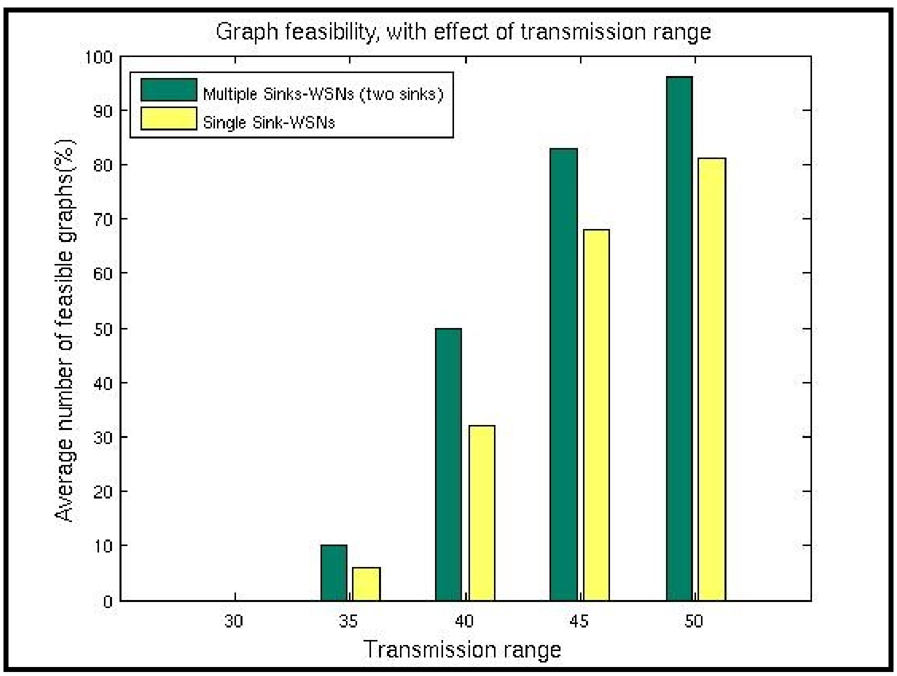

Figure 5.4: Graph feasibility, with effect of transmission range: Number of nodes $= 40$, Network load $= 40$ source nodes.

5.1.5.1 Result Analysis

First, the figure 5.4 shows that for both MS-WSNs and SS-WSNs, 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 will route through the least number of hops (since our routing scheme find routes that maximize the network life time). Therefore, when the transmission range is high, the hop length is low, then, nodes are more likely to route through fewer number of hops, resulting in less contention. Thus, graphs with high transmission range result in more feasible rate solutions. Second, our routing approach on MS-WSNs achieves a greater number of graph feasibility of rate solutions than the routing approach LP-1 on SS-WSNs.

5.2 Network Lifetime Evaluation

In this section, we evaluate the performance of our routing approach for MS-WSNs in terms of network lifetime by comparing it to the performance of the routing approach LP-1 proposed for SS-WSNs. Note that unlike the previous section, the routing approach now considers MAC contention constraints. In the rest of section, we present our simulation setup and method, and then, we study the network lifetime with the effect of the following parameters: number of sinks deployment in such networks, network load, average node degree, and transmission range.

5.2.1 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 is assumed to generate fixed data traffic with a rate requirement of $R_i^k = 0.0005$ bits per second and send to sink k. As in subsection 5.1.1 we assume that the medium capacity W is 1 bit per second. We assume that $B_i(t_0) = 1$ Joule. All simulated MS-WSNs graphs are connected. $IEEE802.11$ MAC protocol [20] is utilized for our simulation. $IEEE802.11$ protocol says that node i cannot send and receive simultaneously because of the radio contention. Moreover, if node i is in communication with node j, then all nodes within the same communication range of i or j cannot communicate. For simulating LP-1 on SS-WSNs, one sink is randomly employed. Unlike MS-WSNs, here in SS-WSNs, all source nodes generate and send data traffic to the sink. Again, unlike in subsection 5.1.1, here, the routing scheme considers MAC contention constraints in order to ensure the physical feasibility of the routing solution.

5.2.2 Effect of Number of Sinks on Network Lifetime

We now examine the effect of the number of sinks on network lifetime. The number of source nodes is set to 40. The transmission range is set to 35 meters. The network load is 40 source nodes. The number of sink nodes is varied from one sink to four sink nodes. Figure 5.5 shows the average network lifetime versus the number of sink nodes.

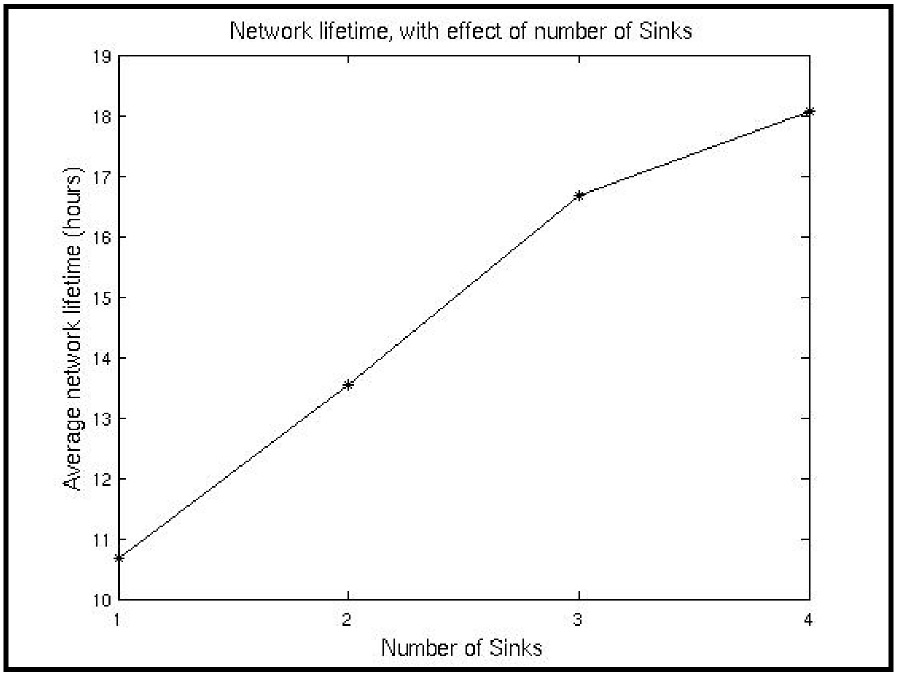

Figure 5.5: Network Lifetime, with effect of number of sinks: Number of sensor nodes $=40$, Network load $= 40$ source nodes, Transmission range $= 35$.

5.2.2.1 Result Analysis

As expected, our routing scheme simulated over MS-WSNs achieves longer network lifetime than LP-1 simulated over SS-WSNs. Figure 5.5 shows that as the number of sink nodes increases, the lifetime of the network increases. We briefly analyze the result as follows: as the number of sink nodes increases, the workload around the sink decreases. To illustrate, when only one sink is deployed, the nodes around the sink have to forward all the messages to the same sink; therefore, their energy resources are consumed fast and deplete quickly. As a consequence, this results in short network lifetime due to early node failures. However, when four sink nodes are deployed over the network area the traffic load is balanced between the four sinks. Therefore, the nodes that are neighbors to each sink k has to forward only the data traffic that has to be destined to the specific sink k. As a result, nodes can live longer due to less energy consumption.

5.2.3 Effect of Average Node Degree on Network Lifetime

In this experiment, we study the effect of average node degree on the network lifetime. We also compare between the routing approaches for SS-WSNs and MS-WSNs. The transmission range is set to 35 meters. Also, the network load is set to 30 source nodes. The average node degree is varied by varying the number of nodes from 30 to 70. In this experiment, we consider two sink nodes as MS in WSNs. Figure 5.6 shows the network lifetime when varying the number of sensor nodes.

5.2.3.1 Result Analysis

First, our approach outperform LP-1. Second, regardless of whether the routing scheme is applied for single sink or multiple sink WSNs, as the average node degree increases, network lifetime increases. Again, the higher the average node degree, the higher the path alternatives to route through, due to the increased number of neighbors. However, low average degree means that nodes are likely to have a limited number of paths due to the low number of neighbors which result in early node failure, thus, shorter network lifetime.

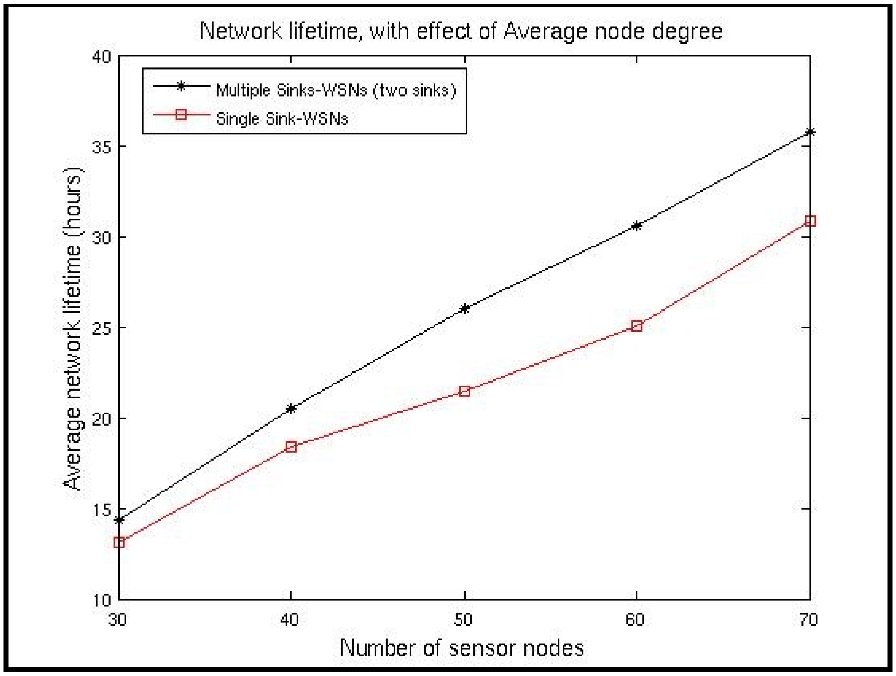

Figure 5.6: Network Lifetime, with effect of average node degree: Network load = 30 source nodes, Transmission range = 35.

5.2.4 Effect of Network load on Network Lifetime

In Figure 5.7, we study the performance of network lifetime with the effect of network load by comparing it with LP-1. The transmission range is fixed and equal to 35 m. Also, the number of sensor nodes is fixed and equal to 40. We vary the network load by varying the number of source nodes as the following: 5, 10, 15, 20, 25, 30, 35, and 40. We also consider two sink nodes for MS- WSNs.

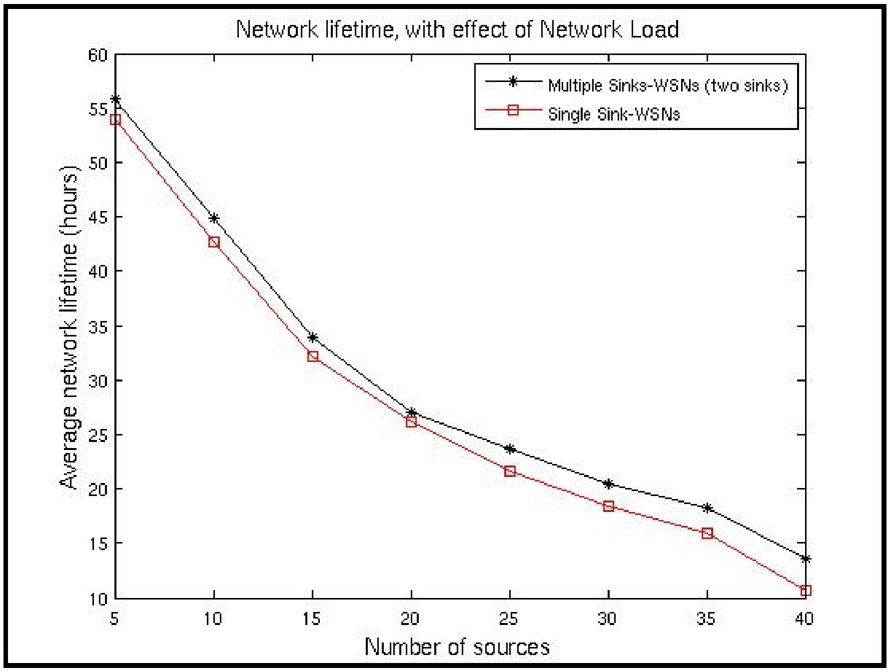

Figure 5.7: Network Lifetime, with effect of Network Load: Number of sensor nodes $= 40$, Transmission range $= 35$.

5.2.4.1 Result Analysis

The figure shows that under the effect of network load, our approach in Two sink-WSNs gives a slightly better lifetime performance than LP-1 in one sink networks. Also it shows that regardless of whether the routing approach is applied for single sink or multiple sink WSNs, when the network load increases, network lifetime decreases. This is because when the network load is high, the number of source nodes that need to generate and forward their own traffic as well as their neighbors' traffic is high, which leads to fast energy depletion resulting in network lifetime decrease.

5.2.5 Effect of Transmission Range on Network Lifetime

Now, we investigate the network lifetime with the effect of transmission range by comparing our routing approach in MS-WSNs to LP-1 in SS-WSNs. We consider and simulate the following transmission ranges: $30, 35, 40, 45,$ and 50 meters. The number of sensor nodes is 40. The network load is equal to 40 source nodes. We also consider two sink nodes as MS in WSNs. Figure 5.8 shows the network lifetime when varying the transmission ranges.

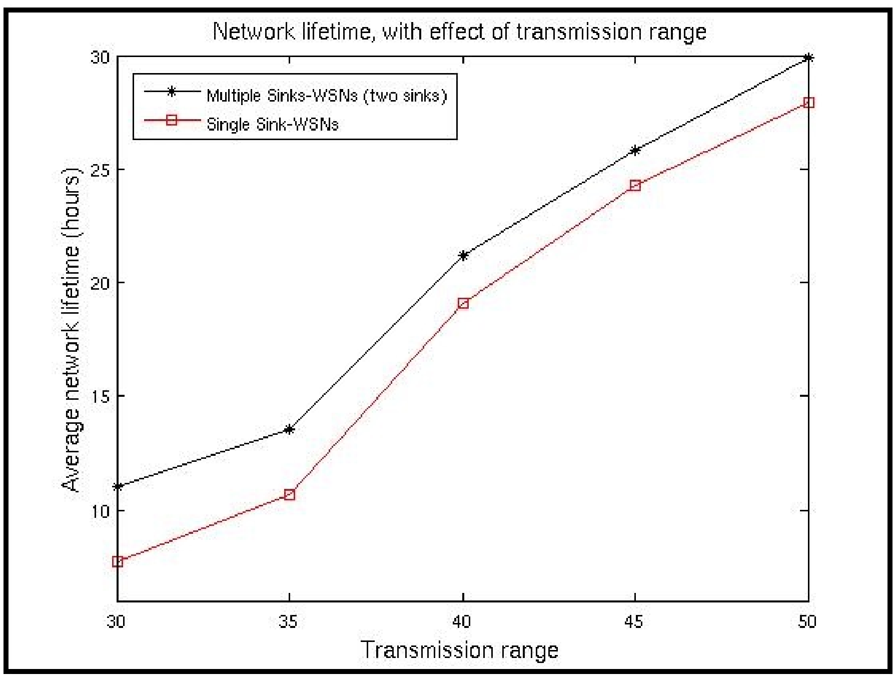

Figure 5.8: Network Lifetime, with effect of transmission range: Number of nodes $= 40$, Network load $= 40$ source nodes.

5.2.5.1 Result Analysis

Figure 5.8 shows that for both MS-WSNs and SS-WSNs, as the transmission range increases the network lifetime increases. This is because when the transmission range is long, the average node degree is high (i.e more neighbors). In this case, nodes have more alternatives to route through. On the other hand, when the transmission range is low, nodes have fewer number of neighbors,(low average node degree). In this case, nodes are most likely to route through the same nodes to reach the sink, thus, they almost send traffic through the same route. This, in turn, leads to fast energy consumption of some nodes and consequently shorter network lifetime. Under the effect of transmission range, our approach simulated over MS-WSNs achieves better lifetime performances than LP-1 simulated over SS-WSNs. The performance deference is low when the average node degree is low (e.g. 30 nodes). However, as the average node degree increases the performance deference between the two approaches increases.

5.3 Practical Aspects and Limitations–A Discussion

Implementation. From the implementation point of view, since the sinks are assumed to have infinite amount of energy, in our proposed approach, one of the sinks is designated to be a leader, and hence, responsible for solving the linear programming problem. After solving the problem, the leader sink broadcasts the rate vector solution, X, to the sensor nodes. Once a sensor node i receives X, it forwards any packet destined to sink k to its neighbor j with a forwarding probability p_{ij}^k equal to

$$p_{ij}^k = \frac{x_{ij}^k}{\sum_{l \in N_i} x_{il}^k} \tag{5.1}$$

The routing process (where the leader sink solves the routing problem and sends the rates to the sensor nodes) repeats after every T seconds. Nodes use the rate solutions to forward packets for the next T seconds. Note that during the initial phase, the leader sink does not know each node's battery information, R_i^k, nor does it know its neighbor list. Therefore, sensor nodes need to broadcast this information to the leader sink in order for it to solve the routing problem. For later phases and if needed, they send their state information using the same route decided by the sink in order for the sink to re-compute the routing process.

Overhead. One of the aspects of the proposed technique that has not been addressed in this work is message overhead. In order for the leader to solve the linear program, each sensor node needs to send information (like battery levels, list of neighbors, etc.) to the leader. Also, once the leader solves the linear program, it needs to broadcast the obtained solution to the sensor nodes. This process incurs message overhead. This overhead depends on how often this process repeats. If the network is static (or almost), then it is anticipated that such an overhead can be insignificant, since this process will take place only a very limited number of times. However, if the network is dynamic (nodes move, links fail, etc.), message overhead can be significant, and hence, it needs to be accounted for carefully in the solution approach. This work assumes that the network is static, and hence, this overhead is minimum.

Multiple sinks. Now the question that arises is what would be the optimal number of sinks? In terms of overhead, as the number of sinks increases, the computational complexity of solving the linear program increases as well. Message overhead, however, will not worsen when the number of sinks is increased. In terms of performance, as the number of sinks increases, the lifetime of the network is expected to prolong. But this increase in lifetime will flatten out eventually with the increase in the number of sinks. Deployment and right placement of sinks can play a huge role when it comes to performance. Although in this work sinks are deployed randomly in the network, investigating and studying the right placement of sinks can improve lifetime significantly. This issue is left for future research.

Decentralization. Our routing solution is based on a centralized approach where the sinks are responsible for the computational processing. This approach works fine with static and small-sized networks. However, for mobile and/or large-scale networks, centralized approaches may be inefficient. Investigating methods to solve this problem in a decentralized manner is left for future work.

Chapter 6: CONCLUSION

Multiple sinks can be deployed in WSNs to increase the network lifetime and to increase the physical feasibility of the routing solution. Moreover, designing a routing approach that is cross-layer aware is crucial to insure feasibility of the rate solution obtained by solving the routing problem. In this paper, we propose a cross-layer aware routing scheme for maximizing the lifetime in MS-WSNs. 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 show that, regardless of wether the routing scheme simulated in MS-WSNs or in SS-WSNs, the rate solutions obtained may not be feasible. However, simulation results show that the rate solutions obtained under our proposed routing scheme for WSNs with multiple sinks are more likely to be feasible than for WSNs with single sink. In addition, simulation results show that our proposed routing scheme for MS-WSNs achieves longer lifetime than the one proposed for SS-WSNs.

There are several directions for future work. We have defined the network lifetime as the time until the first node runs out of energy. However, more useful network lifetime definition can be considered. For example, it can be defined as the time until 5 or 10% of nodes run out of energy. Also, the routing problem can be formulated such that the optimal placement for the sinks is determined. Alternatively, a cross layer aware routing approach for MS-WSNs can be designed with multiple channel access capability.

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