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Title: Energy-Efficient Routing for Delay-Constrained Data Traffic in Linear Wireless Sensor Networks

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Linear wireless sensor networks (LWSN) are special class of wireless sensor networks where sensor nodes are deployed in a straight line. Monitoring industrial pipelines, railroads, tunnels, power lines, and borders are applications of LWSNs. Wireless sensors are tiny devices with limited energy resources; therefore, efficient energy routing in LWSNs is critical. In this work, contention-aware routing schemes for lifetime maximization in time-sensitive and rate-constrained LWSNs are proposed. Furthermore, a LWSN is simulated and the behavior of lifetime against various network parameters is analyzed.

Energy-Efficient Routing for Delay-Constrained Data Traffic in Linear Wireless Sensor Networks

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Hani Alesaimi, Author

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All praise be to Allah alone, the most beneficent, the most merciful, the well-known by his ultimate generosity. He, who removed the depths of darkness with his guidance, brought to life the nations with his revelations and completed his all-encompassing favors on us. Blessings and peace be upon his final prophet, the example to be followed by all believers and the leader of the righteous.

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to the memory of my father, Saeed Alesaimi

Chapter 1: Introduction

1.1 Wireless Sensor Networks

Wireless sensor networks (WSN) [1] have been a promising technology for over a decade now. Progressive developments in miniature electromechanical systems, digital electronics, and radio communications opened doors for a wider range of uses for WSN [1]. A typical WSN consists of a large number of sensor nodes that are randomly deployed in an area of interest in order to monitor, capture and upload environmental attributes to a remote monitoring center for further analysis and actions. Such sensors are usually tiny in size and have very limited resources and capabilities. These sensors can be used to capture various types of environmental attributes including temperature, humidity, motion, pressure and mechanical stress. They typically communicate in a multi-hop fashion where every sensor rely on its neighbors to forward its messages to the network gateway. The gateway is typically called (Sink) which is a device that are collecting all incoming sensors messages and forwarding them to the monitoring center. Sensors miniature form factor enhanced deployment process in many of the WSN applications but on the other hand, it has a negative impact on the sensor local resources such as power, computational capabilities and memory [1]. Sensors have limited and typically not convenient to be replaced or recharged source of energy. Hence, low-power operation is an important requirement for WSN [1]. Energy in WSN is generally consumed by sensing, processing or communicating [2] and although WSN could benefit from a combined consideration of power consumption of signal processing, MAC and communication protocols [2], the scope of this work only considers communication energy consumption.

1.2 WSN Applications

WSN applications are virtually unlimited. It is being used in military for monitoring resources, battlefield surveillance, reconnaissance of opposing forces, targeting and damage assessment. In the environment for forest fire detection, biocomplexity mapping, flood detection and precision agriculture. In health for monitoring human physiological data, tracking doctors and patients and drug administration. In homes for automation, security and smart environments. In industry for inventory control, infrastructures monitoring, condition base monitoring and vehicle tracking [1]. Almost all WSN application can be classified by the type of data being collected into event detection (ED) and spatial process estimation (SPE) [2]. In ED the network is detecting certain events and reporting it to the sink according a predefined thresholds while in SPE the network monitors a whole area of interest for a given physical phenomenon characteristics [2]. Due to the numerous varieties of WSN applications, network requirements and characteristics could vary significantly. Environmental monitoring requires high energy efficiency with low data rates and one-way communication while industrial applications on the other hand demands additional reliability and robustness, security and interoperability with high-data rates and minimum communication delay [2].

1.3 Linear Wireless Sensor Networks

A linear wireless sensor network (LWSN) [3] is a special class of wireless sensor networks (WSN) [1] where sensors are deployed in a straight line as shown in figure 1.1. In [3, p. 1671], a LWSN is defined as "*a new category of WSN where the nodes are placed in a strictly linear or semi-linear from*". LWSNs exist in a wide variety of applications such as industrial pipelines condition monitoring [4–6], railroads, tunnels, power lines, and borders monitoring [3]. In typical WSNs, the deployment of nodes is random but in LWSNs, the topology of the network is predetermined. Although generic WSN routing techniques can be implemented for LWSN, customized protocols that utilize linearity of the topology would improve network performance. WSN techniques like flooding and network discovery might not be necessary in LWSN since the topology is already known. Other techniques such as *Jump always* and *Redirect always* [7] would perform better in LWSNs due to the topology of the network.

In a typical LWSN, all generated data traffic will be forwarded to the sink by a limited number of sensors, i.e. sensors adjacent to the sink. Thereby, those sensors will rapidly lose their energy and impact network performance [8,9]. Therefore, the network must distribute data traffic load intelligently in order to properly consume energy and prolong its lifetime. On the contrary, data traffic generated by nodes far from sinks will have to be relayed through many sensors and endure extended delays. For time-sensitive applications like oil and gas pipelines monitoring, it is critical to report pipelines status within a certain delay margin [4]. Therefore, the network routing protocol should balance energy consumption while ensuring data traffic is being delivered within the accepted delay margin. In this work, energy-efficient routing schemes for delay-constrained data traffic in linear wireless sensor networks are proposed. A LWSN is simulated and the behavior of lifetime against varying network parameters/metric is analyzed.

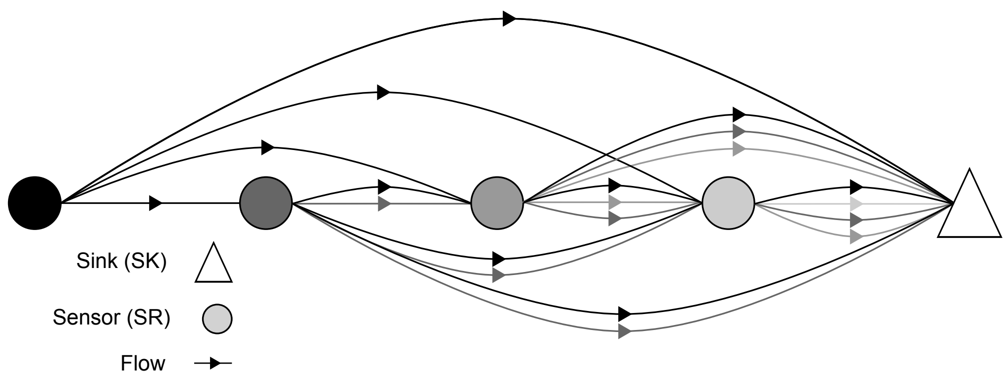

Figure 1.1: Linear wireless sensor network

Chapter 2: Literature Review

In [10], Ehsan *et al.* proposed a network lifetime maximizing MAC-aware schemes for routing rate-constrained traffic in WSN with a single sink. In [11], Xuguang *et al.* proposed a LWSN routing algorithm for monitoring roads post natural disasters. Caneva and Montessoro in [12] proposed a bidirectional wireless communication scheme called Wireless Wire (WiWi) with a contention-free MAC protocol as a virtualization of wire based links. In [13], Liu and Mohapatra studied the deployment of LWSN and addressed the problem of finding the optimal number of nodes given the initial amount of energy in each node and the required lifetime of the network and proposed a close-to-optimal greedy algorithm for deploying nodes in LWSN. Hossain *et al.* in [8] proposed a deployment scheme that enforces equal energy dissipation by each node per each data gathering cycle, and introduced a network energy metric that corresponds to the percentage of consumed network energy at the end of its lifetime. In [14], Chen *et al.* proposed a time-efficient MAC protocol (LC-MAC) for LWSNs to address extended end-to-end delay in power lines monitoring systems. Zimmerling *et al.* in [15] derived a theoretical lower bound for the optimal energy consumption in LWSNs with Poisson distributed sensor nodes in rail roads monitoring applications. Considering channel characteristics, radio components and distribution of nodes, they proposed two routing protocols (MERR) and (AMERR) to minimize energy consumption in LWSNs. In [16], Stoianov *et* *al.* proposed PipeNet, a water pipelines leakage detection system based on Intel's mote. Guo *et al.* in [17] studied nodes deployment techniques that maximize network lifetime in LWSNs for oil pipeline monitoring. They formulated a single-sink LWSN with discrete power-level sensors as a mixed integer linear program, and proposed equal-power consumption placement heuristics to maximize the network lifetime.

Chapter 3: System Model

3.1 Network Model

A LWSN is modeled as a directed acyclic graph $G = (\mathcal{M}, \mathcal{F})$ where $\mathcal{M}$ and $\mathcal{F}$ are finite nonempty sets of all nodes and all flows in G respectively. Let $\mathcal{N}$ and $\mathcal{K}$ be the subsets of $\mathcal{M}$ that contain all sensor nodes (SR) and all sink nodes (SK), respectively. Each flow in $\mathcal{F}$ corresponds to an ordered pair $(n, m)_s^l$ such that SR n is able to receive traffic originated from node l and forward it to SR m in order to be relayed to SK s. At any given time, each SR i must associate with a single SK s and forward its data traffic toward s. It is assumed that at any given time, there exists at least one path from every SR to a single SK.

3.2 Communications Model

For the flow $(n, m)_s^l \in \mathcal{F}$, SRs m, n and l must be associated with s and since n and m are associated with s and are able to communicate with each other, they are considered to be neighbors. At any given time, each SR i must associate with a single SK s and forward its generated data traffic toward s. An *active* SR is one that is able to communicate with its neighbors. An *inactive* SR is unable to communicate either because it has consumed all of its energy or it is isolated due to other inactive SRs along the path to the SK. Every SK is assumed to have an infinite amount of energy and to upload SRs data to the monitoring center via a separate network. Additionally, all SKs are assumed neither to generate nor forward any data in the LWSN. Finally, it is assumed that each SR has only one communication interface and all SRs are communicating on a single channel.

3.3 Nodes Placement

In G, all nodes are deployed equidistantly and all SRs are identical in term of capabilities and internal resources. The first SK is always placed on one edge of the network and the second SK is always on the other edge. Any additional SKs are placed in the middle of the network. Each edge SK is collecting data traffic from a single direction while each intermediate SK is collecting data from both directions. The network is divided into multiple sections S_y where each section corresponds to a SK side as shown in figure 3.1. Note that y is defined as $2|\mathcal{K}| - 2 \geq y \geq 1$ where $2|\mathcal{K}| - 2$ is the total number of sections in the network G. Each SK must associate with at least one SR in each section. Let $|\mathcal{N}|_{S_y}$ denote the number of SRs in a section S_y such that,

$$|\mathcal{N}|_{S_y} = \begin{cases} \left\lceil \frac{|\mathcal{N}|}{2|\mathcal{K}|-2} \right\rceil, & \text{if } y \leq (|\mathcal{N}| \bmod (2|\mathcal{K}|-2)), \\ \\ \left\lfloor \frac{|\mathcal{N}|}{2|\mathcal{K}|-2} \right\rfloor, & \text{otherwise.} \end{cases}$$

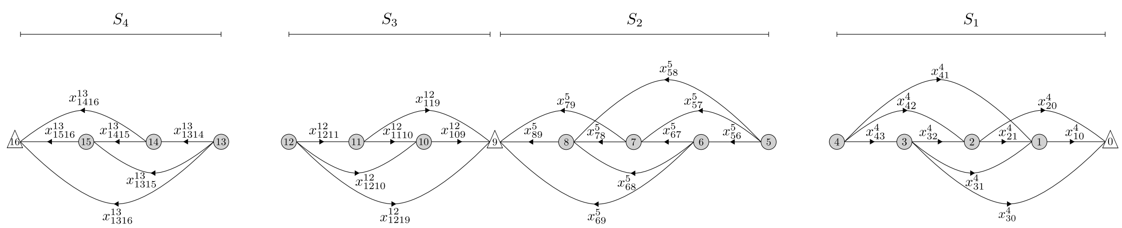

Figure 3.1: A LWSN of 14 SRs and 3 SKs

Chapter 4: Routing

In this section, routing constraints are established and routing is formulated as a linear optimization problem. In G and for each flow $(i,j)_s^k \in \mathcal{F}$, let x_{ij}^k denote the forwarding data rates in bits per second and $X = [x_{ij}^k]_{1 \le i,j,k \le |\mathcal{N}|}$ denote the rate vector of all data rates. When SR i is transmitting, it is assumed to send L-bit messages at an average rate of R_i. Whenever a SR consumes its entire energy, the network will seize to function. Hence, the network lifetime T is defined as the time taken by the first SR to consume its entire energy. The wireless channel capacity W is defined as the maximum data rate the wireless medium can support. In this work, the goal is to find an optimal vector X that maximizes the network lifetime T subject to a set of routing constraints. All routing constraints will be established in the next section.

4.1 Routing Constraints

For X to be feasible in rate-constrained and time-sensitive LWSNs, the following constraints must be satisfied,

4.1.1 Flow Balance Constraints

For each SR i, the sum of all outgoing data rates must equal the sending rate of SR i; i.e.,

$$\sum_{j \in \mathcal{N}} x_{ij}^{i} = R_i; \quad \forall i \in \mathcal{N}. \tag{4.1}$$

For each SK s, the sum of all incoming data rates must equal the sum of all sending data rates of all transmitting SRs that are associated with s. That is,

$$\sum_{i,k \in \mathcal{N}} x_{is}^{k} = \sum_{k \in \mathcal{N}} R_k; \quad \forall s \in \mathcal{K}. \tag{4.2}$$

The sum of all SR k flows forwarded to SR j must equal the sum of all k flows forwarded by j. That is,

$$\sum_{i \in \mathcal{N}} x_{ij}^{k} = \sum_{q \in \mathcal{N}} x_{jq}^{k}; \quad \forall j, k \in \mathcal{N}. \tag{4.3}$$

Each SK s is assumed to neither generate nor forward any data traffic in the network. That is,

$$x_{si}^{p} = 0; \quad \forall\, i \in \mathcal{N}, \quad \forall s, p \in \mathcal{K}. \tag{4.4}$$

Finally, all data rates must be positive; i.e.,

$$x_{ij}^{k} \geq 0; \quad i, j, k \in \mathcal{N}. \tag{4.5}$$

4.1.2 Energy Consumption Constraints

SRs consume energy while sensing, processing or communicating. In this work, only communication energy is being considered. The widely used energy consumption model of [18] is used. Let c_{ij} denote the amount of energy required to transmit one bit from node i to node j. If the distance between i and j is denoted by d_{ij} then $c_{ij} = \beta d_{ij}^{\gamma}$ where β accounts for energy dissipated in the transmitter amplifier and γ is the *path loss exponent*. In networks with a clear line-of-sight, γ is typically 2 and in dense urban areas it can go up to 6 [19]. In this work, γ is set to 2. Let $B_i\left(t\right)$ be the amount of energy SR i has at at time t. According to our definition of the network lifetime T in section 3, $B_i(T) \geq 0$ must hold for every SR in order for the network to be functional. Hence, if the LWSN is deployed at time t_0, then

$$B_i\left(t_0\right) \geq T \times \underset{j,k\in\mathcal{N}}{} c_{ij} x_{ij}^{k} \tag{4.6}$$

must hold for every SR i. Inequality (4.6) is not linear in variables T and x_{ij}^{k}. But when letting $F = 1/T$, it can be equivalently rewritten as

$$F \geq \frac{1}{B_i(t_0)} \times \underset{j,k\in\mathcal{N}}{} c_{ij} x_{ij}^{k}, \tag{4.7}$$

yielding an inequality that is linear in variables F and x_{ij}^{k}. Note that minimizing F is equivalent to maximizing the lifetime T.

4.1.3 Medium Contention Constraints

In this work, The IEEE 802.11 MAC protocol [20] is being implemented. IEEE 802.11 MAC dictates that if SR i is communicating with SR j, all nodes within the transmission range of either i or j can not communicate. Let the set of flows $\mathcal{F}$ be modeled as the undirected graph $C = (\mathcal{F}, \mathcal{L})$ where $\mathcal{L}$ is the finite set of all distinct contending pairs of flows in $\mathcal{F}$. The graph C is referred to as *flow contention* graph [21]. Let Ψ_{ij}^k be the set of all flows that contend with the active flow $(i,j)_s^k$; i.e., $\Psi_{ij}^k = \left\{ (p,q)_s^h \in \mathcal{F} : \left((i,j)_s^k, (p,q)_s^h \right) \in \mathcal{L} \right\}$. The rate vector X is feasible if, for all $i, j, k \in \mathcal{N}$, the following medium contention constraints hold [21],

$$x_{ij}^k + \sum_{(p,q)_s^h \in \Psi_{ij}^k} x_{pq}^h \leq W; \quad \forall\, s \in \mathcal{K} \tag{4.8}$$

4.1.4 Delay constraints

For time-sensitive WSN applications, data must be successfully delivered to the SK within a certain amount of time or it would otherwise be useless. Let L^k denote SR k's number of bits (size of one message) to be delivered to the SK, and L_{ij}^k denote SR k's number of bits (out of the L^k bits) to be forwarded over flow $(i,j)_s^k$ at the rate x_{ij}^k. It easily follows, from the flow balance constraints given above, that $L_{ij}^k = (x_{ij}^k / R_k) L^k$.

Let $\tau_{ij}^k = L_{ij}^k / x_{ij}^k$ be the time taken by i to send L_{ij}^k over a flow $(i,j)_s^k$ at the rate x_{ij}^k. Replacing L_{ij}^k by its value given above yields $\tau_{ij}^k = L^k / R_k$. Note that τ_{ij}^k does not depend on i, j, and hence, let $\tau_{ij}^k = L^k / R_k \triangleq \tau^k$ for all i, j.

Also, by letting L_i^k denote the total amount of SR k's data bits forwarded by i; i.e., $L_i^k = L^k \sum_{j \in \mathcal{N}} x_{ij}^k / R_k$, the time τ_i^k taken by SR i to forward these L_i^k bits over all its flows is $\tau_i^k = L_i^k / \sum_{j \in \mathcal{N}} x_{ij}^k = \tau^k$. Note that the time it takes any intermediate SR i to forward a SR k's data bits to another SR j is the same regardless of i (same for all intermediate SRs) and regardless of j (same for all SR i's neighbors).

Let $\bar{\tau}^k$ denote the time needed for the network to deliver SR k's L^k data bits to the SK. Letting h^k denote the number of hops along the longest path from SR k to its destined sink, then $\bar{\tau}^k = h^k \tau^k$.

Let τ_{th} be the maximum tolerable delay for every SR to deliver its messages to its SK such that,

$$\bar{\tau}^k \leq \tau_{th}; \quad \forall\, k \in \mathcal{N}. \tag{4.9}$$

Let $\mathcal{P}^k$ be the set of all flows that when utilized to forward SR k's bits, the maximum delay of SR k's data delivery does not exceed the threshold, τ_{th} (i.e., inequality (4.9) is met). Thus, in order for SR k to meet its delay bound, $x_{pq}^k = 0$.

Note that if the network is required to deliver all messages to the SK in the least possible time, each SR must continuously and exclusively communicate with its furthest neighbor. In this case and because there will be only one possible routing scheme, the network lifetime can be straightforwardly calculated. Note that τ_{min} is used to refer to this case throughout this thesis.

4.2 Routing Formulation

The routing problem is now formulated into two linear programs: LP1 and LP2.

4.2.1 LP1

Minimize F

Subject to:

Flow balance constraints: (4.1)–(4.5)

Energy consumption constraints: (4.7)

Medium contention constraints: (4.8)

Delay constraints: (4.9)

LP1 provides the optimal data rates vector X that maximizes the network lifetime subject to all constraints.

4.2.2 LP2

Minimize F

Subject to:

Flow balance constraints: (4.1)–(4.5)

Energy consumption constraints: (4.7)

Medium contention constraints: (4.8)

LP2 provides the optimal data rates vector X that maximizes the network lifetime subject to all except delay constraints. LP2 distributes the data traffic load between all flows to ensure efficient energy consumption and maximum network lifetime. The achieved lifetime with LP2 can be considered as an upper bound on the lifetime achieved under LP1.

Chapter 5: System Performance

5.1 Simulation Setup

Simulation results are conducted using MATLAB. The simulated LWSNs consists of N SRs and K SKs. The network length is set to $TD = 1000$m and all nodes are deployed equidistantly along a straight line as described in Section 3. The wireless medium capacity W is assumed to be 1 bit per second, and each SR is assumed to be sending data bits at a rate of $R = 10^{-2}$ bits per second (i.e., $R_k = R = 10^{-2}$ for all SR k). It is assumed that $L^k = L$ for all SR k (and hence $\tau^k = \tau = L/R$ for all SR k). The maximum transmission range of each SR is $TR = 100$m, and the maximum accepted delay is $\tau_{th} = 2\tau$. Each SR k has initially an energy level of $B_k(t_0) = B = 10^5$ Joules. All network parameters are listed in Table 5.1. The network lifetime behavior is studied while considering the following metrics/effects:

5.1.1 Effect of MAC contention

When maximizing the network lifetime without contention-awareness, the optimal data rates might not be practically feasible. Therefore, the behavior of the network lifetime with and without MAC constraints in a high traffic load LWSN is studied.

Table 5.1: Network Parameters

Parameter	Description	Value
N	Number of sensors	50
K	Number of sinks	6
R	Sending data rate	0.01 bit/sec
B	Initial energy	1E+05 Joule
β	Amplifier energy	1E-02 Joule/bit/m^2
γ	Path loss exponent	2
η	Nodes density	0.056 nodes/m
TR	Transmission range	100 m
TD	Total distance	1000 m
W	Channel capacity	1 bit/sec
τ_{th}	Maximum tolerable delay	2τ

5.1.2 Effect of SRs maximum transmission range

The maximum transmission range of each SR is varied while the number of SRs and SKs is kept unchanged. Increasing the maximum transmission range will increase the number of neighbors of each SR; thus, additional flows will be available to be utilized for maximizing the network lifetime. The maximum transmission range is varied between 36m to 126m.

5.1.3 Effect of the number of SKs

The number of SKs, K, is varied while the maximum transmission range and the number of SRs are kept the same. Increasing the number of SKs decreases the distance between nodes and the average number of SRs per section. Except for single-SK networks, each added SK increases the total number of sections by two and changes SRs association. Although the total generated data traffic in the network is unchanged, increasing the number of SKs will reduce the data traffic per SK. K is varied from 5 to 26.

5.1.4 Effect of SRs Density

The number of SRs is varied while the maximum transmission range and number of SKs are unchanged. Increasing the number of SRs decreases the distance between nodes and increases the average number of SRs per section. The latter impact is less than when increasing the number of SKs because it does not change SRs associations and affects only the section where the new SR is placed in. Because each SR is sending data at a rate R, increasing the number of SRs will increase the total traffic in the network. Therefore, the total amount of traffic in the network is controlled by fixing the number of sending SRs. Let $Sensor$ be an operating mode for active SRs in which active SRs will be generating their own data traffic and relaying other SRs' data traffic as well, while $Relay$ is the mode in which active SRs are not generating but only relaying other SRs' data traffic. By fixing the number of $Sensor$ SRs, the total amount of generated data in the network remains unchanged. All SRs in the $Sensor$ mode are always assumed to be at the edge of each section furthest from SKs. Let η denote SR density; i.e., $\eta = (N + K)/TD$.

5.1.5 Effect of network tolerance to SRs failures

When maximizing the network lifetime for time-insensitive LWSN, the routing scheme will distribute the energy consumption between all SRs such that by the end of the network lifetime, the residual energy in each SR will be zero. When time sensitivity is important, the routing scheme will overuse some of the SRs in order to meet delay requirements and rapidly consume their energy. This will make the network non-operational—according to our definition of network lifetime—in despite of the amount of residual energy in the remaining active SRs. In this study, the validity of our network lifetime definition is examined by observing the amount of extra lifetime that can be achieved if the network is able to tolerate more than just the first failing SR. When a SR runs out of energy, it is ignored and new optimal data rates for the remaining network are determined. The new optimal data rates are calculated based on the status of the network when that SR ran out of energy. This is repeated until all SRs in a section run out of energy.

5.2 Results Analysis

In this section, results are presented and analyzed.

5.2.1 MAC contention

Figure 5.1 illustrates the behavior of network lifetime against η. Initially at a lower density, each SR has only one neighbor; hence, there is only one possible routing path. Thus, MAC contention has no impact on lifetime. As density increases, SRs will have more neighbors and MAC contention will have an impact. The results here show that when considering MAC constraints, the network has a shorter lifetime compared to when MAC constraints are not considered. This is expected as having more constraints leads to less routing options, yielding smaller network lifetimes. However, what is very important to mention here is that when not considering MAC constraints, the routing solution, though provides higher lifetime, may not actually be feasible. Similarly in figure 5.2, when varying the SR transmission range, the maximum achieved network lifetime without considering MAC contention, expected to be higher due to lesser constraints, might not be feasible either.

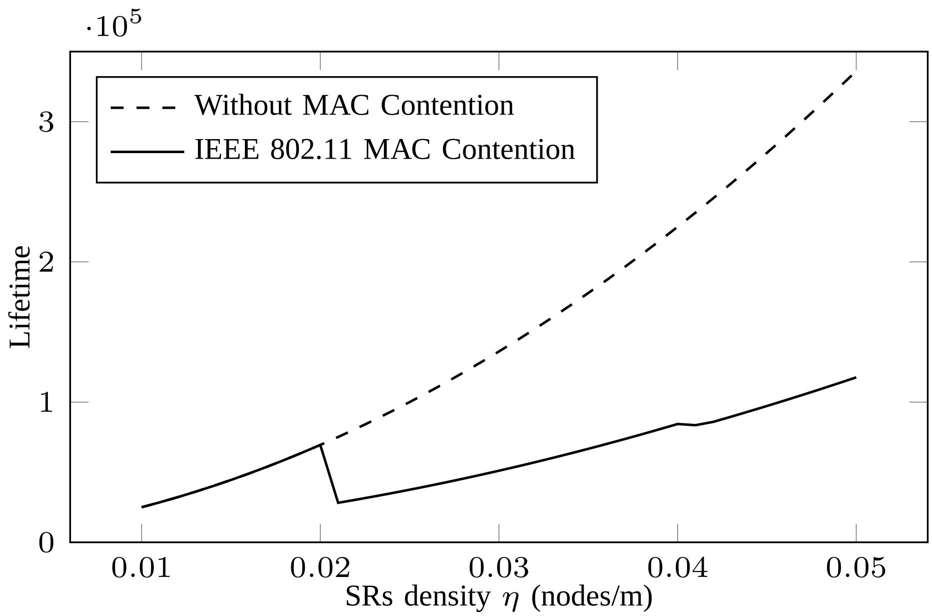

Figure 5.1: Impact of MAC contention constraints on achievable network lifetime when varying SRs density

5.2.2 SRs maximum transmission range

Figure 5.3 illustrates the effect of increasing the maximum transmission range on the network lifetime. Recall that LP1 gives maximum network lifetime when delay constraints are considered; LP2 gives maximum lifetime but without considering delay constraints; and τ_{min} corresponds to network lifetime while ensuring the minimum possible delay. Although SRs are able to communicate with more neighbors when the transmission range is increased, the lifetime achieved under LP1 and LP2 does not increase significantly. This is because communicating with those new further-away neighbors has a high energy cost, forcing the routing scheme to avoid communicating through them. On the other hand, the network lifetime achieved when ensuring the minimum possible delay, τ_{min}, is constantly decreasing as the transmission range increases. This is expected because SRs are always communicating with furthest neighbors, and hence, as new neighbors come within their range (due to increasing the transmission range), they will immediately route all their data traffic through these new neighbors, thereby consuming more energy.

5.2.3 Number of SKs

In figure 5.4, network lifetime behaves similarly in all scenarios when the number of SKs is increased. When more SKs are added to the network, the distance between nodes decreases and so does the energy cost per flow. Additionally, the number of sections increases and SK associations of most SRs change. It is also observed that by adding more SKs, the lifetime achieved under LP1 approaches that achievable

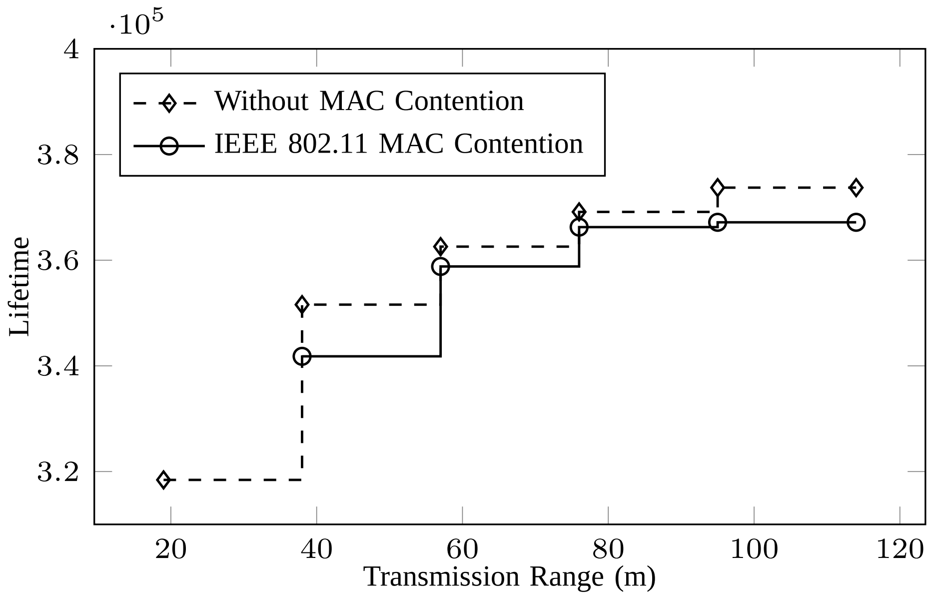

Figure 5.2: Impact of MAC contention constraints on achievable network lifetime when varying SRs transmission range

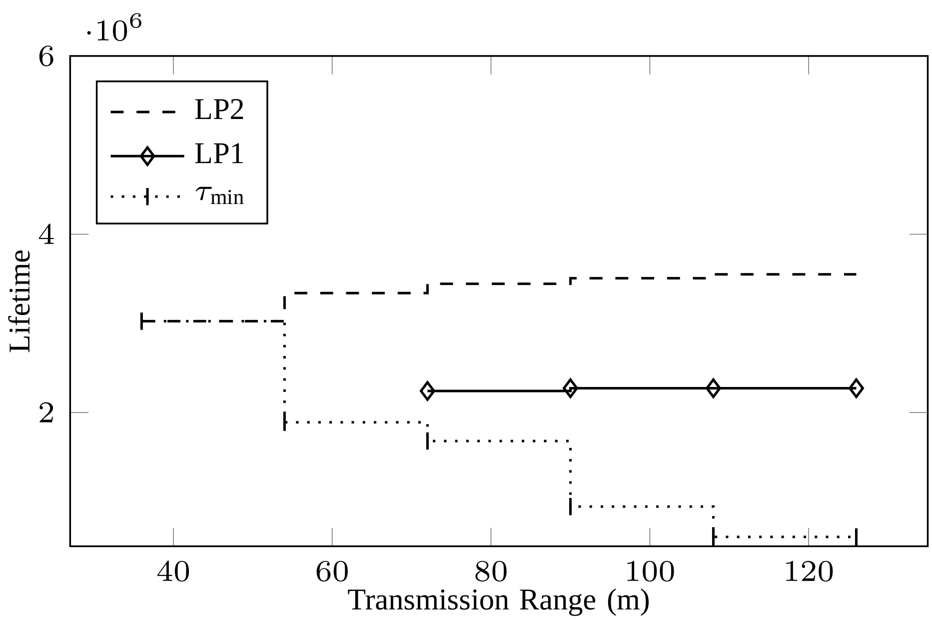

Figure 5.3: Lifetime vs. transmission range

under LP2. This is because the average number of SRs per section decreases and delay constraints become less restrictive. This study can be useful for determining optimal numbers of SKs when designing LWSNs.

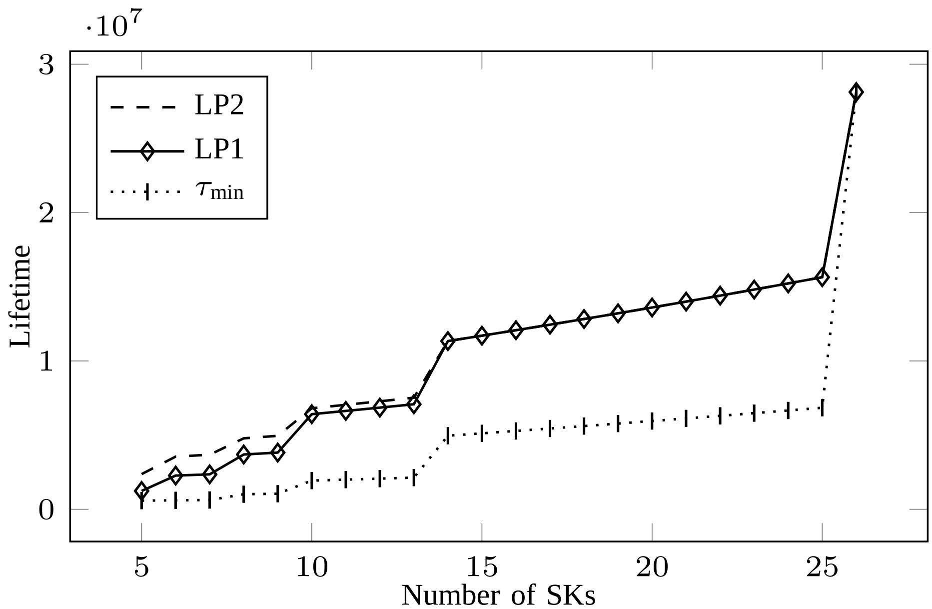

Figure 5.4: Lifetime vs. number of SKs

5.2.4 SRs density

Figure 5.5 illustrates the behavior of network lifetime when varying the number of SRs (i.e., SR density). It is observed that the lifetime achieved under LP2 is constantly increasing when more SRs are added to the network. This is expected as LP2 does not consider delay constraints, and the higher the number of nodes, the greater the chances of increasing network lifetime, provided here that the number of sending SRs is kept the same in the process of increasing the total number of SRs.

By adding more SRs while not increasing the number of sending SRs, the network is basically provided with more energy resources. On the contrary, the lifetime achieved under LP1 remains about the same when the number of SRs is increased. This is because when distance between nodes decreases (due to increasing SR density), SRs consume less energy per the same flow, yielding a (slight) lifetime increase. By adding more SRs, eventually new neighbors will be available at the edge of the transmission range. Typically, those neighbors should be ignored but because delay is considered in LP1, SRs end up communicating with the new neighbors so as to satisfy delay constraints, thus decreasing the lifetime. By adding more SRs, the energy cost per each flow decreases and the network lifetime slightly increases again. As for the network lifetime achieved when ensuring the minimum possible delay, τ_{min}, it exhibits behavior that is similar to what has been observed in figure 5.3, and the same explanations apply here as well. Overall, it is observed that for time-sensitive LWSNs (when delay constraints are considered), increasing the number of SRs does not always increase the network lifetime.

5.2.5 Network tolerance to SRs failures

Figure 5.6 shows the lifetime behavior when assuming that the network can still be operational even when some SRs die; that is, when the network tolerates SR failure. First, note the network lifetime achievable under LP2 is the same because when maximizing lifetime without considering delay, the optimal rate solution is such that all nodes deplete their energy resources at the same time. For the network lifetime achieved when ensuring the minimum possible delay, the extension in network lifetime is minimal but slowly increasing. Since each SR will route its entire traffic to the same neighbor, few SRs in the middle of each section will lose their energy faster than others. This is because those SRs will be relaying more traffic. After few iterations and when the length of the isolated parts is longer than the transmission range of nodes, parts of each section will be isolated. This can be observed in figure 5.6 when the lifetime suddenly and significantly increases because the total traffic in the network dramatically decreases due to isolated sections. When considering the lifetime under LP1, the routing scheme will balance energy consumption so SRs will run out of energy in groups. The increase in lifetime is due to isolated sections and fewer active nodes in each section. Figure 5.7 shows the optimal data rate per each flow in the network for LP1. In the first iteration, most of the flows in the network are utilized and energy consumption is distributed. In the second iteration, all SRs are either dead or isolated and there is only one active flow in every section.

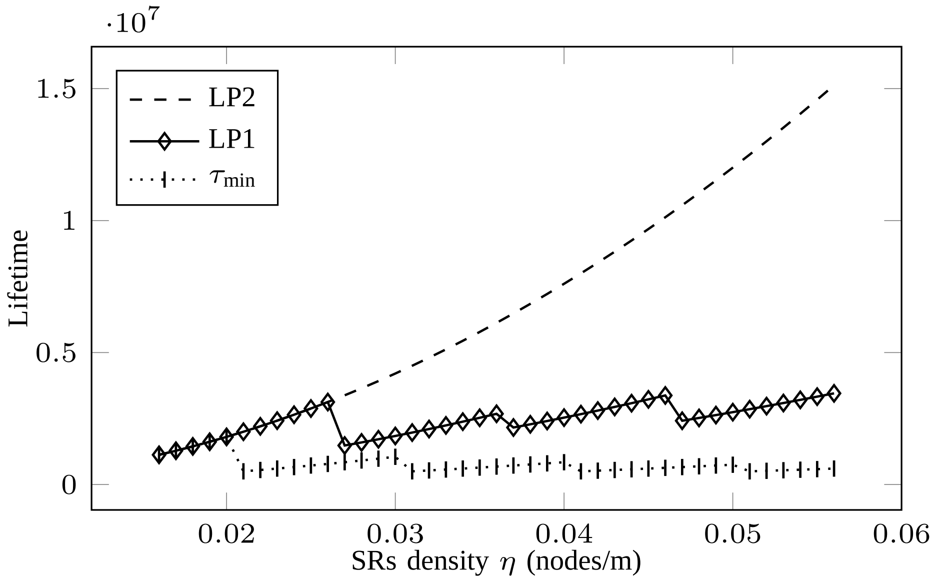

Figure 5.5: Lifetime vs. SRs density η

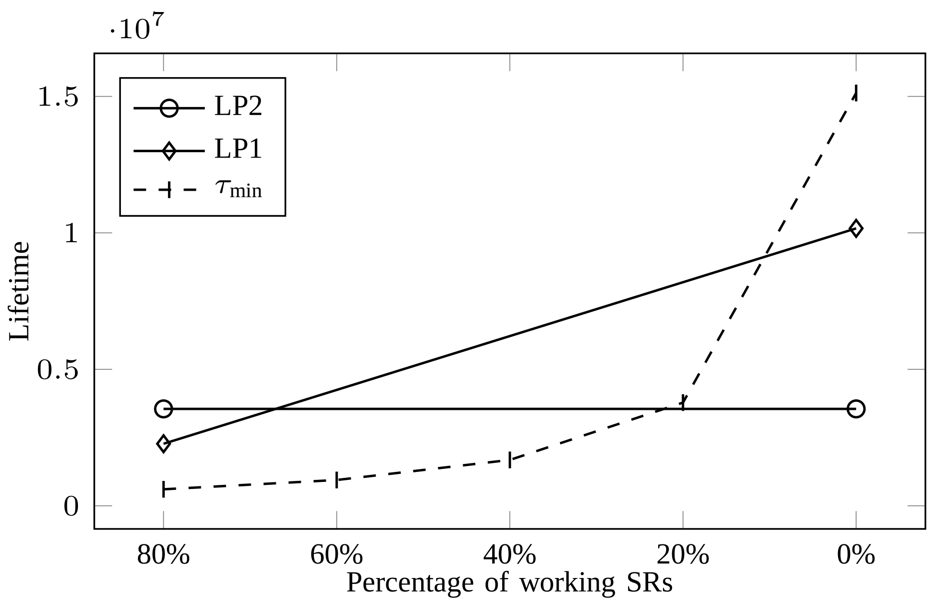

Figure 5.6: Lifetime vs. network failure tolerance

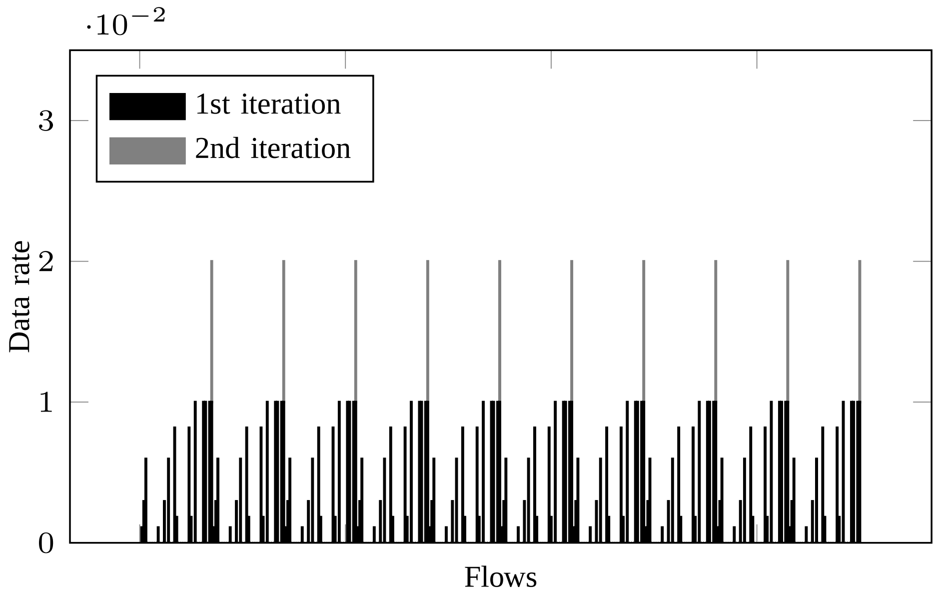

Figure 5.7: Flows data rates per iteration for LP1

Chapter 6: Conclusion

In this work, energy-efficient routing schemes for lifetime maximization in delay-constrained LWSNs are proposed. The behavior of network lifetime against different effects/metrics is analyzed. It was shown that MAC contention awareness is important for optimal data rate feasibility. It was also shown that increasing transmission range of SRs does not necessarily increase the lifetime. Moreover, our results show that controlling SRs maximum transmission energy levels is not needed since the optimal data rates will optimize energy consumption anyway. It was shown that for time-sensitive LWSNs, increasing the number of SRs does not always increase the network lifetime since by increasing SRs density per section, SRs will have to transmit to further neighbors to satisfy delay constraints and as a result, they consume more energy. Finally, it was shown that when nodes failures are tolerated, network lifetime can be extended.

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