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LEACH-SM: A PROTOCOL FOR EXTENDING WIRELESS SENSOR NETWORK LIFETIME BY MANAGEMENT OF SPARE NODES

by

Bilal Abu Bakr

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Advisor: Leszek T. Lilien, Ph.D.

Western Michigan University
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LEACH-SM: A PROTOCOL FOR EXTENDING WIRELESS SENSOR NETWORK LIFETIME BY MANAGEMENT OF SPARE NODES

Bilal Abu Bakr, Ph.D.

Western Michigan University, 2011

Operational lifetime of a wireless sensor network (WSN) depends on its energy resources. Significant improvement of WSN lifetime can be achieved by adding spare sensor nodes to WSN. Spares are ready to be switched on when any primary (a node that is not a spare) exhausts its energy. A spare replacing a primary becomes a primary itself.

The LEACH-SM protocol (Low-Energy Adaptive Clustering Hierarchy with Spare Management) proposed by us is a modification of the prominent LEACH protocol. LEACH extends WSN lifetime via rotation of cluster heads but allows for inefficiencies due to redundant sensing target coverage. There are two energy-consumption inefficiencies in LEACH. The first one, the *hotspot problem*, is due to extra duties of cluster heads (as compared to regular nodes) that increase their energy usage. The second inefficiency is redundant data transmissions to cluster heads (made by regular nodes covering targets redundantly). Both inefficiencies are reduced by using spares in LEACH-SM.

LEACH-SM has three main features. First, from the subset of WSN nodes that provide redundant area coverage, we select the optimal collection of spares (to maximize extension of WSN lifetime). We overcome race conditions and deadlocks that can occur

during the spare selection process. The second main feature is deciding how long spares should remain asleep, and which spares should be used as replacements for primaries that exhausted their energy. The third main feature is estimating WSN lifetime as determined by energy consumption of all its sensor nodes.

We provided analytical estimates and comparisons of LEACH and LEACH-SM for simplified cases. We also run simulation experiments (using MATLAB) to compare both protocols for general and complex cases. We studied the impact of the spare ratio and duration of the nap interval of cluster heads on the WSN lifetime for LEACH and LEACH-SM.

Even when no spares are used, LEACH-SM achieves 23% to 48% extension of the average WSN lifetime when compared to LEACH (this is due to switching off redundant nodes in LEACH-SM). When LEACH-SM uses spares, LEACH-SM achieves 183% extension of the average WSN lifetime when compared to LEACH (which is unable to use spares).

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Dedicated to my father Prof. Irshad Ul Hasan

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Bilal Abu Bakr

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1. INTRODUCTION TO THE PROBLEM

A *wireless sensor network* (*WSN*) may be defined as a collection of sensor nodes that usually derive their energy from attached batteries. Typically, the nodes are tiny, disposable, and low-power.

WSN lifetime is the key characteristics for the evaluation of sensor networks. In the literature, there are many definitions of WSN lifetime. We accept the following definition [VDMC08]: *WSN lifetime* is "*the interval of time, starting with the very first transmission in the wireless network during the setup phase and ending when the percentage of reports from sensor nodes fall below a specific threshold, which is set according to the type of the application.*"

In other words, a WSN lifetime can be defined by a threshold $x\,\%$ as follows. A WSN starts its operation with n active *primaries* (primary sensor nodes) and is considered dead when the number of its still working nodes drops below $n \times x\,\%$ (replacement of failed primary nodes by spare nodes may be allowed). In the literature, researchers prove that deployment of *spare* (*redundant*) sensor nodes increases WSN lifetime. E.g., Li *et al.* [LWYW06] discuss deployment of redundant nodes with appropriate scheduling techniques.

We recognize the pivotal importance of *energy-saving* strategies, although *energy-harvesting* approaches [AlGa08, ZZZ10], can also be used, either as an alternative or as a complement.

We divide primaries as either *cluster heads* or *regular nodes* (that is, primary nodes that are not cluster heads). Regular nodes sense and aggregate data, and send them to cluster heads. Both types of primaries are activated at the beginning of normal WSN operation.

If all spares were activated as well, they would provide an above-threshold (more than required) or redundant target coverage at the cost of wasting energy. Therefore, they are switched off initially but are ready to be switched on to replace a primary that exhausts its energy. (A spare helps to replace an exhausted primary only if the spare can cover at least some of the targets that were covered by the exhausted primary.)

To benefit from having spares, they must be properly managed. Mismanagement of spares includes, e.g., allowing redundant and above-threshold target coverage by spares, which increases energy consumption; energy is wasted for transmission of redundant (thus superfluous) data from regular nodes to cluster heads. Therefore, mismanaged spares can shorten WSN lifetime instead of extending it.

WSN lifetime can be prolonged by many techniques, including adaptive data propagation [SuSh10], algorithms that switch between sensor covers [DVCR04], energy-efficient communication protocols [YHE04], clustering [ASSC02], energy level assignment [RGM08], deployment of redundant nodes with appropriate scheduling techniques [LWYW06], energy-aware routing [GDPV03], specialized MAC protocols [YHE02], different topology control techniques [ZDLC09], effective collision avoidance [JiZh06], and high channel utilization [PrGa10].

However, relatively little attention is paid to extending WSN lifetime by proper placement and management of spares.

An application using a WSN typically is not concerned with individual sensor nodes [JBS07]. Instead, the application objective is achieved by the WSN as the whole.

1.1 Using Redundancy for Extending WSN Lifetime

A WSN covers targets of interest within a certain area in order to monitor certain physical phenomena associated with these targets [Dress07]. When a sensor node exhausts its energy and "dies," the targets covered solely by it become uncovered, resulting in a *target coverage hole*. To extend the WSN lifetime, spare sensor nodes can replace exhausted (dead) nodes. The spares must be ready to be switched on when any *primary node* (i.e., a node that is not a spare) fails or uses up its battery power.[1]

Replacing exhausted sensor nodes with spares to enhance the network lifetime is not a simple job; it requires skillful network management. This is our focus. (Also, optimization opportunities provided by good understanding of the semantics of an application served by the WSN can be exploited. But this is beyond the scope of this research.)

1.2 Motivation

The LEACH protocol [Hein00] is a prominent protocol for static sensor nodes that combines the ideas of energy-efficient cluster-based routing (with a cluster head selected in each cluster) and media access with application-specific data aggregation to achieve good performance in terms of WSN lifetime, latency, and application-perceived quality.

---

[1] We consider only node failures due to battery energy exhaustion.

LEACH employs no spares, so all nodes in LEACH are primaries; at any given time some primaries are cluster heads, and others are *regular nodes*—i.e., nodes that are not cluster heads. According to LEACH, all regular nodes within each cluster transmit data packets to their own cluster heads periodically.

There are two energy-consumption inefficiencies for cluster heads. The first one, the *hotspot problem*, is due to extra duties of cluster heads that increase their energy usage. The solution proposed by the LEACH protocol is well-planned rotation of the cluster head role among all nodes in a cluster, and ensuring that all nodes serve as a cluster head exactly only once during WSN lifetime. In this way, LEACH tries to even out the long-term energy usage by all nodes in each cluster. However, this protocol does not compensate sufficiently for extra energy consumption by nodes during their cluster head service.

The second inefficiency is redundant data transmission to cluster heads by sensor nodes covering targets redundantly. This results in unnecessary load on cluster heads. LEACH proposes no solution for this inefficiency.

Extra energy consumption by nodes during their cluster head service and transmission of redundant data to cluster heads may be due also to faulty spare management. If the spares are properly managed, that is, not more than the required number of sensor nodes is active, then we can reduce both inefficiencies.

1.3 Outline of the Proposed Solution: The LEACH-SM Protocol

LEACH incorporates randomized rotation of cluster head. The randomized rotation of the cluster head role among the nodes in a cluster does not fully compensate for the extra energy expenditure by a sensor node during the interval in which it serves as a cluster head.

Our LEACH-SM ("SM" stands for "Spare Management") protocol modifies LEACH by enhancing it with an efficient management of spares. As LEACH, it is designed for static sensor nodes and static targets.

LEACH-SM deals with both energy-consumption inefficiencies of LEACH by adding *spare selection* phase, to the original LEACH protocol. During the spare selection phase we select nodes that should become spares. After deciding to become a spare, the spare goes Asleep to conserve energy. This results (as will be explained) in extending WSN lifetime.

Changing the status of nodes that provide redundant target coverage[2] from a primary to a spare reduces both inefficiencies of LEACH. First, it reduces the redundant data transmissions to the cluster head (the first inefficiency), by having some nodes as spares, which reduces the amount of sensed data sent to cluster heads. Second, it reduces the hotspot problem (the second inefficiency), by shortening the active interval of cluster heads (which is the result of having some spares, that is, fewer primary nodes).

So, even just identification of nodes that should become spares increases the overall WSN lifetime. (Other aspects of spare management can extend WSN lifetime further.)

The LEACH-SM protocol achieves the following objectives:

- Extending WSN lifetime (which—under our definition of WSN lifetime—is equivalent to extending the period of the above-threshold coverage).
- Reducing transmission of redundant data to cluster heads.

---

[2] A node provides *redundant target coverage* if all targets covered by it are already covered by other nodes.

- Allowing each sensor node in all clusters to decide in parallel if it becomes a primary or a spare.
- Maintaining scalability by using only local information for the above optimizations.

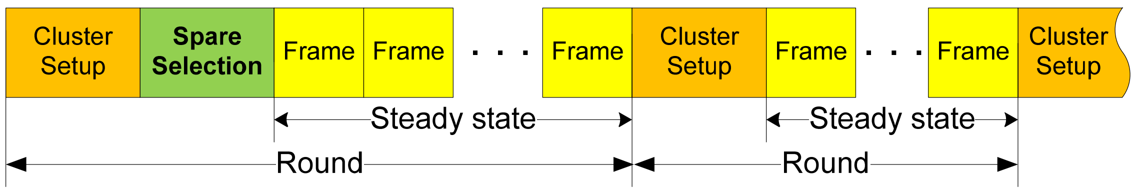


Figure 1.1. Rounds, phases, and frames for LEACH-SM, including the added spare selection phase. Note that spare selection is done only once in WSN lifetime.

LEACH-SM adds a phase, called the *spare selection* phase, to the original LEACH protocol. It follows the setup phase, and is followed by the regular operation of the WSN, as shown in Figure 1.1. (Regular WSN operation is divided into frames, during which nodes follow cycles of awake and nap intervals.) The *Decentralized Energy-efficient Spare Selection Technique* (*DESST*) is run during this spare selection phase.

DESST, run in parallel on all WSN nodes in all clusters, allows each node to decide whether it should become a spare. It is done in such a way that the above-threshold target coverage is maintained by the WSN. After deciding to become a spare, the node goes Asleep to conserve energy. As the result, WSN lifetime is extended.

1.4 Organization

Section 2 provides background information. Section 3 discusses research goals. Section 4 discusses related work. Section 5 presents LEACH and a detailed analysis of its inefficiency problems. Section 6 presents LEACH-SM – the proposed solution to the LEACH inefficiency problem. Section 7 discusses management of spares. Section 8 discusses the analytical comparison of WSN lifetime for LEACH and LEACH-SM. Section 9 presents simulation experiments evaluating and comparing LEACH and LEACH-SM. Section 10 draws conclusions and presents future work.

2. BACKGROUND INFORMATION

The basic purpose of wireless sensor network is to collect the measurement of physical values (e.g. barometric pressure, temperature, vibrations, positioning, animal position, vital health signs of a patient, etc.), aggregate this information and transmit it to a base station (called the "sink") for further analysis.

Sensor nodes are a specific class of embedded systems. The description of the composition of a single sensor node is helpful in understanding the significant resource restrictions of sensor nodes. Figure 2.1 illustrates a typical configuration of hardware components within a sensor node.

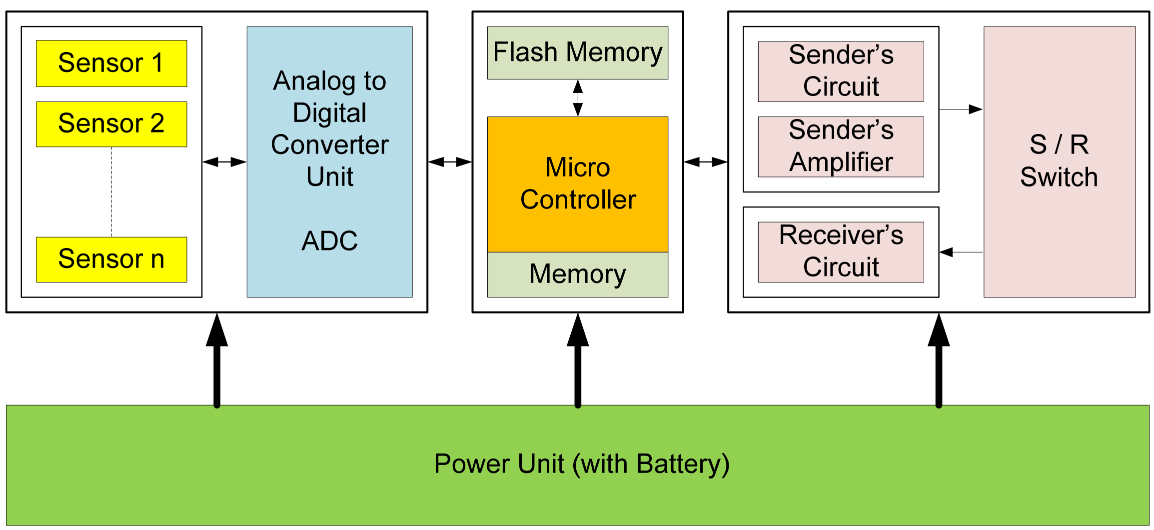


Figure 2.1. Hardware components of a typical sensor node.

A typical sensor node is made up of four basic components: a sensing unit, a processing unit, a transceiver unit and a power unit [ASSC02]. The processing unit is a small micro controller with some associated memory (SRAM) and permanent storage (flash memory). For example, Atmel ATmega 128 is an 8-bit low-power system operating at 16 MHz, with 128 Kbyte flash memory and 8 Kbyte of SRAM [ZLX08]. Wide-ranging computations are not possible for this resource-constrained device.

For wireless data communication, multiple radio technologies and transceivers are used on sensor nodes. Widely used transceivers include the ultra-low-power single chip RF transceiver Chipcon CC1000, operating in the 315/433/868/915 MHz SRD bands, as well as the single-chip 2.4 GHz IEEE 802.15.4 compliant and ZigBee-ready transceiver Chipcon CC2400 [VDMC08]. The radio communication unit can transmit messages with a quite limited throughput to neighboring nodes.

Lastly, battery is the most critical component of the power unit. Its capacity and size are the most challenging operational constraints of the power source. In addition to these challenges [SLZ08], several other considerations for the use of batteries in sensor nodes include energy density, environmental impact, cost, safety, available voltage and charge/discharge characteristics. In this work, we are concerned with battery capacity only.

2.1 Deployment of Wireless Sensor Nodes and Object Coverage

There are two widely used types of deployment techniques for WSNs. First, pre-designed deployment (including as a special case grid placement) is usually performed by human operators and results in a well-planned layout. Second, random deployment is made in the ad hoc fashion, which includes throwing out sensor nodes from a moving vehicle or an airplane. In this research we consider the second case, that is, the random deployment scheme. Recall that we assume static sensor nodes.

2.2 Object Coverage and Connectivity

Coverage is perhaps one of the most significant characteristic in terms of applicability and energy use in WSNs. Two coverage types need to be considered here [Dress07] (cf. Figure 2.2). First, a *sensing range* r_s ("sensor coverage") of a sensor node is the range within which the node is able to measure physical properties of target.

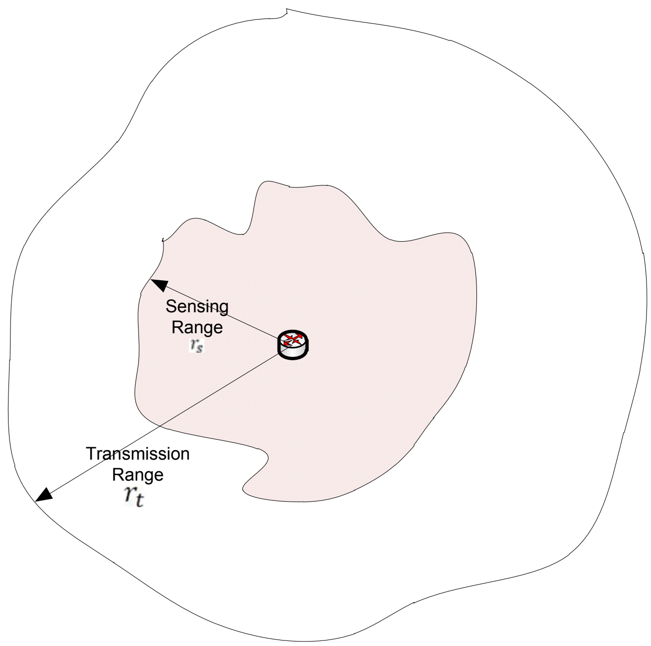


Figure 2.2. Irregular shape for transmission and sensing ranges.

Second, the *transmission range* r_t ("radio coverage") of a sensor node determines network connectivity. Each node has a certain transmission range so that it can reach a next-hop neighbor (as determined by the particular routing protocol).

Two nodes can communicate only when they are in each other's transmission range. WSNs must avoid having *isolated sensor nodes*, that is, nodes that cannot communicate with the base station; this communication is either indirect via other nodes of the WSN, or—in the worst case (because longer-distance communication means larger energy expenditure)—directly. Each sensor node may adjust its transmission range by increasing or decreasing its transmission power, which results in extending or shortening, respectively, the *lifetime of the node*.

To simplify WSN analysis, as is typically done, we assume omnidirectional antennas and regular sensing and transmission ranges. The latter assumption means an ideal circular environment for sensing and transmission (while in practice, they have an irregular shape). We also assume that for each node its transmission range is larger than its sensing range (which, without due precision—since "r's" are not radiuses for irregular shapes—can be symbolically indicated as "$r_t \geq r_s$").

There are two types of object coverage: area coverage and target coverage. *Area coverage* is the ability of a sensor network to cover, or monitor, a geographic area. Therefore, in order to have 100% area coverage each point in the physical region must be within the range of at least one sensor node.

Target coverage deals with monitoring a set of points (targets) that are located within a domain of interest. In order to monitor all the targets within the region, each target must be covered by at least one sensor node. Monitoring a target by more than one sensor node may improve quality of sensing data in noisy environments but, as we have indicated, results in having redundant coverage problems (including redundant data transmissions to cluster heads). In this research, we deal only with target coverage only.

2.3 Definition of SR-neighbor

Let s_i and s_j be two sensor nodes with sensing ranges r_i and r_j respectively, then s_i is said to be *SR-neighbor* of s_j if and only if s_j receives the hello message of s_i.

We define $SRN(s_m)$ as the set of all SR-neighbors of s_m. That is:

$$SRN(s_m) = \{ s_p : \ s_p \in SRN(s_m) \} \tag{2.1}$$

The set of all SR-neighbors of s_m from cluster C_j is denoted by $SRN(s_m, C_j)$, and defined as:

$$SRN(s_m, C_j) = \{ s_p : \ s_p \in SRN(s_m) \ \wedge \ s_p \in C_j \} \tag{2.2}$$

Note that:

$$SRN(s_m) = \bigcup_{j \in \{1,2,3,\dots,N\}} (s_m, C_j) \tag{2.3}$$

We define $SRN^{-}(s_m)$ as the set of all SR-neighbors of s_m except s_m itself. That is:

$$SRN^{-}(s_m) = SRN(s_m) - \{s_m\} \tag{2.4}$$

$TS(s_p)$ denotes the set of targets covered by s_p. Suppose that targets A, B and C are covered by sensor node s_p, then $\mathrm{TS}(s_p) = \{A, B, C\}$.

2.4 Power Modes for Wireless Sensor Nodes

There are two power modes for sensor nodes: the active mode and the passive mode (cf. Figure 2.3.). Cluster heads and regular nodes are in the active mode, whereas spares are in the passive mode.

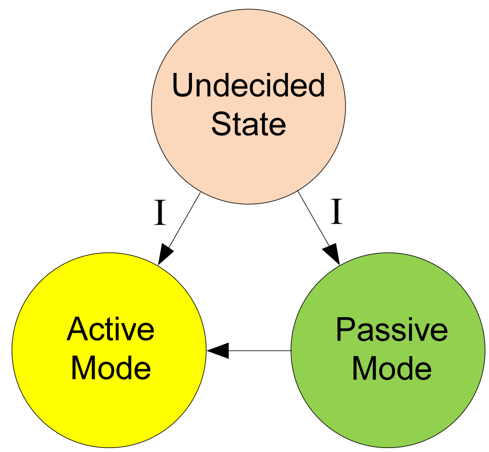


Figure 2.3. State diagram for power modes of sensor nodes. ("I" indicates a transition occurring during WSN initialization.)

2.5 The Duty Cycle for WSN Nodes

Sensor nodes are not always transmitting or receiving data; instead nodes are allowed to be awake or to nap periodically.

The duration of the Awake interval depends, among others, upon the application and the role of the sensor node (cluster head, regular or spare). However, the sensor nodes that are in passive mode (that is, spares) are Asleep till time t (using no energy till that moment), when they awake they enter into awake/nap cycles.

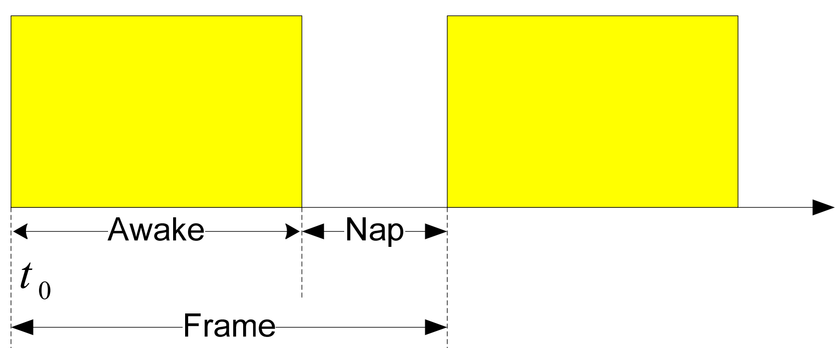


Figure 2.4. Basic frame structure for sensor nodes.

A *frame* is the interval during which each regular node sends one message (consisting of multiple packets) with the sensed data to the cluster head. It includes Awake and Nap intervals. The *frame duration* for a node is the sum of its one Awake interval and one Nap interval [YHE04]. The *duty cycle* of a node is the ratio of the duration of its Awake interval to the frame duration (cf. Figure 2.4).

2.6 WSN Failures and Battery Capacity

There are many reasons for WSN failure. We should know the causes of failure for the sake of prevention. It is rarely practicable to identify a priori all failure causes. The main reasons of WSN failures are as follows:

1. Battery exhaustion: the failure of WSN due to using out all battery energy for a certain number of sensor nodes.
2. A defective MAC protocol: Many MAC protocols have been proposed recently to minimize energy consumption. An inadequate MAC protocol (e.g., one allowing for too many collisions) can cause a premature WSN failure due to faster energy consumption.
3. Deterioration: WSNs can fail due to deterioration of its components. Deterioration is difficult to analyze, because it varies with the type of sensor nodes and the material used.
4. Environmental conditions: The environmental conditions (e.g., flooding, extreme temperatures) play a significant role in WSN failures.

There are many other reasons of WSN failures. In this research we consider only WSN failures due to battery exhaustion in sensor nodes. The restricted battery power of sensor nodes is the major limiting factor that reduces their operating time. We show that the lifetime of WSNs can be increased by efficient scheduling and proper management of sensor nodes in WSNs.

The capacity of a battery can be defined by the amount of charge that it can store. The charge, expressed, e.g., in Coulombs or Ah, can be converted to its equivalent units in terms of current and time.

$$B = I \times t \tag{2.5}$$

where I is current and t is time.

If B and I are known (and I is the average current used), we can calculate how long the battery can last as:

$$t = \frac{B\ [Ah]}{I\ [A]} = \frac{\mathrm{B}}{I}\,[h] \tag{2.6}$$

3. RESEARCH GOALS

We propose the LEACH-SM protocol—a modification of LEACH—to realize the following three most significant goals for extending the lifetime of WSN.

3.1 Goal 1: Optimal Spare Selection

If more than the minimal numbers of sensor nodes than required for above-threshold coverage are active, then WSN lifetime is shortened. To achieve WSN lifetime extension, LEACH-SM adds the *spare selection* phase to LEACH. This phase consists of two intervals: the sensing range neighbor (SR-neighbor) discovery interval, and the DESST execution interval (where DESST stands for *Decentralized Energy-efficient Spare Selection Technique*).

DESST is a spare management technique that, when executed in parallel by all regular nodes, decides whether a given node should become a spare or a regular (*primary node* i.e., a node that is not a spare). At the moment t_0 when the spare selection phase ends, primary nodes are active (that is, Awake or Napping), while the spares are passive (that is, Asleep).

DESST maintains the coverage above the target coverage threshold. DESST consists of: (i) finding the order in which nodes must make the spare/primary decision; and (ii) actually *making* this decision. Since sensing ranges for nodes can cross cluster boundaries, race conditions and deadlocks can occur in Step (ii). We overcome these challenges.

Nodes that became spares provide redundant coverage w.r.t. to the primary nodes. If not put Asleep by DESST, they would send redundant data to cluster heads.

Importance. DESST achieves the following significant objectives: (i) extending WSN lifetime; (ii) allowing nodes in all clusters to make primary/spare decisions in parallel; (iii) reducing transmission of redundant data to cluster heads.

3.2 Goal 2: Management of Spare Nodes after WSN Deployment

To the best of our knowledge, limited attention is paid in the literature to managing spares. This makes our second research goal for LEACH-SM significant. This goal is providing a proper spare management in order to decide: (i) how long the spares should remain Asleep; and (ii) which spare should be used as a replacement for a given primary node that used up all their energy.

We propose that spares are initially Asleep, and wake up[3] to enter the Awake-Nap cycles at time *t*[4, 5] (*t* is estimated by DESST during the spare selection phase). During its very short Awake intervals, each spare checks with its cluster head if it is needed to replace a primary. Very short Awake intervals imply very long Nap intervals, which results in lowered energy consumption by spares that are no longer in the Sleep state.

[3] Spares wake up themselves (using a standard built-in time). A cluster head could wake up a sleeping spare only if special hardware were available.

[4] As primary nodes exhaust their energy, the target coverage can decrease from 100% to the threshold value. If spares are unavailable, the coverage will go down to X% at certain time t_X. We set $t = t_X$.

[5] The larger is *t* the more energy is saved by spares. However, if *t* is too large, some exhausted nodes would have no spares ready for replacing them.

Note that the end of each Awake interval for a spare coincides with the end of the (much longer) Awake interval for its cluster head.

In contrast to spares, primaries must follow the cycles of Awake and Nap intervals from the moment t_0 of WSN deployment. Their Awake intervals are much longer, and their Nap intervals are shorter than for spares after time t.

Importance. A proper management of spare nodes saves their energy, making them available for a longer time for replacing failed primaries. This extends WSN lifetime.

3.3 Goal 3: Estimating the Lifetime of WSN

A good estimate of WSN lifetime is critical for planning WSN applications. The power management problem associated with WSNs is conceptually a simple, based on supply and consumption. In practice, it is complicated by many factors affecting WSN lifetime. Providing WSN lifetime estimate requires: (i) calculating lifetime for primary nodes and spares; (ii) calculating duty cycles for all types of nodes; and (iii) estimating lifetime of node batteries.

Importance. A good estimate of WSN lifetime has a fundamental importance for planning WSN applications.

4. RELATED WORK

In this section we briefly report on the work performed on the presented problem by other researchers. A number of topology management algorithms and schemes have been proposed to increase WSN lifetime. This section discusses briefly the main results of the most relevant work related to lifetime extension and power management for WSNs.

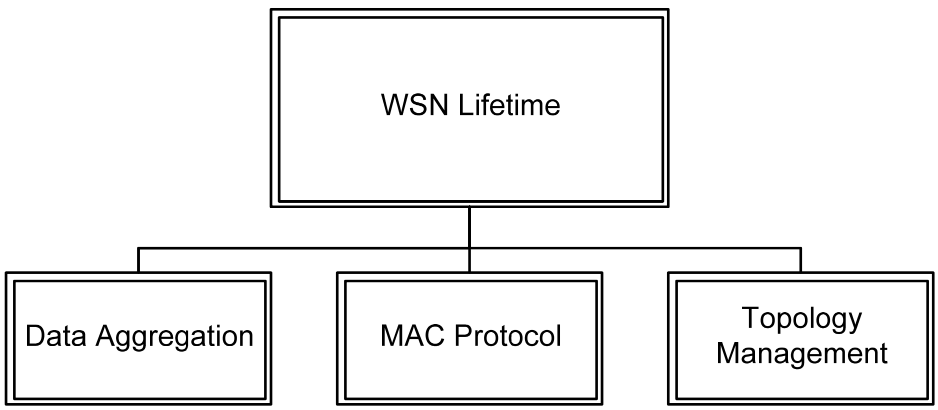


Figure 4.1. Three main categories of solutions extending WSN lifetime.

The solutions extending WSN lifetime can be divided into three main classes (cf. Figure 4.1): (i) Data Aggregation solutions, (ii) MAC Protocol solutions, and (iii) Scheduling of sensor nodes solutions..

The design a MAC protocol deals with energy aware routing, low duty cycle, energy-efficient communication protocols, etc. Data aggregation solutions deal with techniques like coding (combines incoming data), adaptive data propagation, etc. Topology management solutions consider efficient scheduling and management of individual sensor nodes, clustering of nodes, energy level assignment to nodes, and deployment of redundant nodes, appropriate scheduling techniques, etc.

There is a lot of research being done on solutions in the areas of Data Aggregation and MAC Protocol, but less research in the area of WSN topology management in terms of scheduling and management of sensor nodes.

Heinzelman [Hein00] designed and implemented Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol for WSN. LEACH uses a clustering architecture. Each cluster elects a cluster head. For balancing energy load in the network, LEACH rotates the energy-thirsty function of the cluster head among all the nodes in a cluster. To avoid data transmission collisions, LEACH uses a time division multiple access (TDMA) protocol. The major characteristics of LEACH include randomized, adaptive, and self-configured cluster formation; localized control for data transfer; low-energy media access; and application-specific data processing for data aggregation or compression.

Zhang et al. [ZLX08] introduced the Efficient Power and Coverage Algorithm (EPCA) that puts the redundant sensor nodes into the sleep mode while maintaining the sensing field fully covered. The idea of EPCA is that any sensor node turns itself off if the so called coverage degree of its neighbors is not affected. Authors introduce two modes in the scheduling phase: active and passive. Every sensor node in the passive mode wakes up periodically to receive beacon messages from sensor nodes that are in the active mode. It is not clear which sensor node will decide first to go to sleep. Moreover, the periodic wake-up schedule for the sensor nodes those are in the passive mode remains unspecified.

Zhou *et al.* [ZXWP06] present energy efficient data dissemination (EEDD) protocol. They consider two-level node activity schedules: coarse and fine. At the coarse schedule level, only a necessary set of working sensor nodes are kept Awake, and other sensor nodes are enter the long-term sleep state. All sensor nodes decide their state through a detection process. In the detection process, a sensor node playing the detecting node function broadcasts a detecting message to its neighbors to detect the number of active nodes within its detection range. If a working node in the detection range of the message sender has energy higher than a pre-specified value $E_{gridhead}$, it sends back a response message. If the number of response messages received by the detecting node exceeds a pre-defined threshold, the detecting node considers itself a redundant and enters the long-term sleep state; otherwise, the detecting node enters the working mode.

The protocol proposed by Gallais *et al.* [ACSS06] deploys sensor nodes randomly over a square area. An active WSN node belongs to one of the k layers, where a layer provides a full coverage of the sensing area. In other words, the sensing area is covered redundantly k times k layers.

Suppose that we look at the protocol at the moment that $j<k$ layers have already been created. But there are still nodes that do not belong to any of these j layers. Let Node A be one of these nodes that do not belong to any layers yet. Node A listens to activity messages from its neighbors. For example, the neighbor Node B belonging to Layer i includes in its activity message the identifier i of the layer to which it belongs. In this way, node A finds out all layers that cover its location and the degree of coverage redundancy for its location. Suppose that node A finds out that its location is covered 2 times and the required degree of coverage redundancy must be 3. Node A turns itself ON

and sends the activity message to all its neighbors stating that it belongs to layer 3. Any redundant node that does not belong to Layer 1 or Layer 2 can now decide to join Layer 3. This is the basic idea of the protocol for assuring that sensing area is k-covered.

Lai *et al.* [LWYW06] propose a genetic algorithm to find an approximate solution for the NP-complete Disjoint Set Covers (DSC) problem. They consider extending the WSN lifetime by dividing all sensors into disjoint sensor subsets, or sensor covers, and each sensor cover needs to satisfy the coverage constraints. Only one sensor cover is active to provide the functionality and the remaining sensor covers are in the sleeping mode. Once the active sensor cover runs out of energy and consequently cannot maintain coverage constraints, another sensor cover will be selected to enter the active mode and provide the functionality continuously. The more sensor covers we can find, the longer sensor network lifetime will be prolonged. Finding the optimal number of sensor covers can be solved via transformation to the DSC problem.

Chamam *et al.* [ChPi907] address the problem of maximizing the WSN lifetime under the area coverage constraint. They propose a scheduling mechanism that, for every time slot during the operating period, calculates an optimal covering subset of sensor nodes; only those nodes are activated for the given period and the remaining ones are put to sleep.

Ren *et al.* [RGM08] propose an initial energy assignment (IEA) strategy, which increases WSN lifetime by providing different initial energy levels to different sensor nodes. The nodes that play more energy-consuming functions get more initial energy. This is in an attempt to assure that all nodes, independent of their function, use up their available energy at (nearly) the same moment.

Dasika *et al*. [DVCR04] present an algorithm that determines the schedule for transitioning sets of sensor nodes between active and inactive states that satisfy user-specified performance constraints. Each sensor node remains in the undecided state until all of its “weaker” neighbors choose their state (a node is “weaker” when it has less energy).

Esseghir *et al.* [EsPe08] optimize the wireless sensor network lifetime under a reliability constraint. They introduce a function that links reliability to the average amount of energy consumed by the network when reporting an event to the base station. Based on this function, they bring out the required number of successive readings to be performed in order to optimize both network lifetime and reliability.

They also give an altered definition of reliability in order to maximize the network lifetime by relaxing the reliability restriction. In this case, the reliability is defined w.r.t. the number of non-reported events.

Mak *et al*. [MaSe09] they study different WSN protocols based on various WSN lifetime definitions. They classify WSN protocol and different WNS lifetime definitions. With the help of simulation they compare performance of WSN protocols.

Hasegawa *et al.* [HKTM09] propose a routing reconfiguration method based on an autonomous optimization of the dynamics of mutually connected neural network which minimizes its own energy function using autonomous and distributed computing. They also show that the proposed method can optimize routes for maximizing the lifetime of the sensor network, without any centralized computing nodes.

Xiong *et al.* [XLY09] prove that the problem of maximizing the lifetime of a data-gathering sensor network, which is defined as the number of rounds until the first node depletes its energy, is NP-complete. They then formulate it as an integer program to get a suboptimal result. They further propose a polynomial-time and provably near-optimal algorithm to reduce the tremendous computation and storage cost of integer programming. Finally, they evaluate the efficiency of their algorithms by extensive experiments.

5. DETAILED ANALYSIS OF THE INEFFICIENCY PROBLEM IN LEACH

This section discusses in detail inefficiencies in LEACH, which can be eliminated to extend WSN lifetime. It calculates the duration of the Awake interval, the duty cycles, and average current drawn by cluster heads and regular nodes in LEACH. Next, it calculates WSN lifetime for LEACH and its two main variants, named LEACH-C (LEACH-Centralized) and LEACH-F (Fixed Cluster, Rotating Cluster-Head). Finally, it calculates residual WSN lifetime for LEACH, LEACH-C, and LEACH-F.

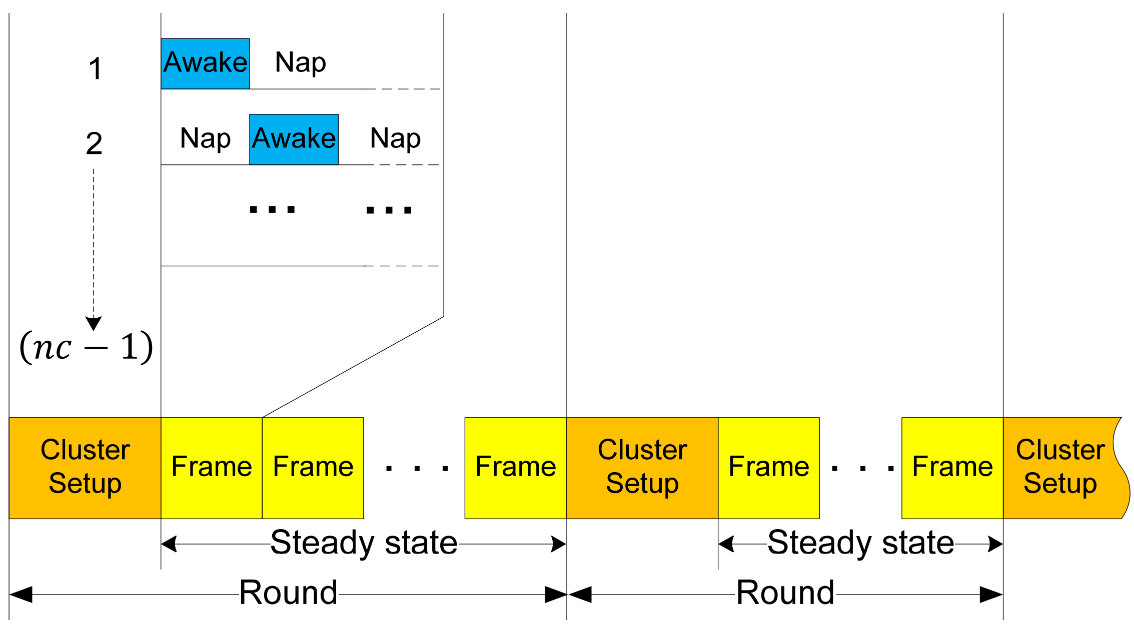


Figure 5.1. Rounds, phases, and frames for one cluster (with a cluster head and nc regular nodes) in LEACH.

5.1 Timeline of LEACH

The operation of LEACH is divided into *rounds* as shown in Figure 5.1. Each round is further subdivided into a *(cluster) setup phase* and a *steady state phase.* In each round, a new cluster configuration is formed,[6] and a new cluster head is selected from among the nodes that have not served as a cluster head in previous rounds. The lifetime estimate algorithm in LEACH assures with a high probability that LEACH will not run out of candidate cluster heads that did not serve as a cluster head yet. In other words, for each round an appropriate node that did not serve as a cluster head yet is found with a high probability.

The number of rounds in LEACH is determined as N/K, where N is the number of WSN nodes, and K is the expected number of clusters.

The steady state phase is further subdivided into frames. A frame is the interval during which each regular node sends one message (consisting of multiple packets) with the sensed data to the cluster head. Note that the number of frames per round is an optimization parameter that is used to maximize WSN lifetime in LEACH (also in LEACH-SM).

As shown in Figure 5.1, the frame duration for a node is the sum of either: (i) one Awake interval and one Nap interval (for Nodes 1 and $nc - 1$ in Figure 5.1); or (ii) one Awake interval and two Nap interval (for Nodes 2, 3, …, $nc - 2$ in Figure 5.1). Note that the total time spent napping is the same for cases (i) and (ii).

A *round duration* depends on the number of frames contained within the round. The number of frames for a given round in LEACH is determined in a way that

[6] In each round, the number of clusters is determined anew. That is, in general, a different number of clusters is formed in each round.

(statistically) ensures that each node's energy is sufficient to allow the node to be a cluster head once (during one round) during WSN lifetime and to be a regular node during the remaining $R-1$ rounds of WSN lifetime.

5.2 The Inefficiency in LEACH

As discussed earlier, the main reason of inefficiencies in LEACH is the inefficient use of redundant sensor nodes.

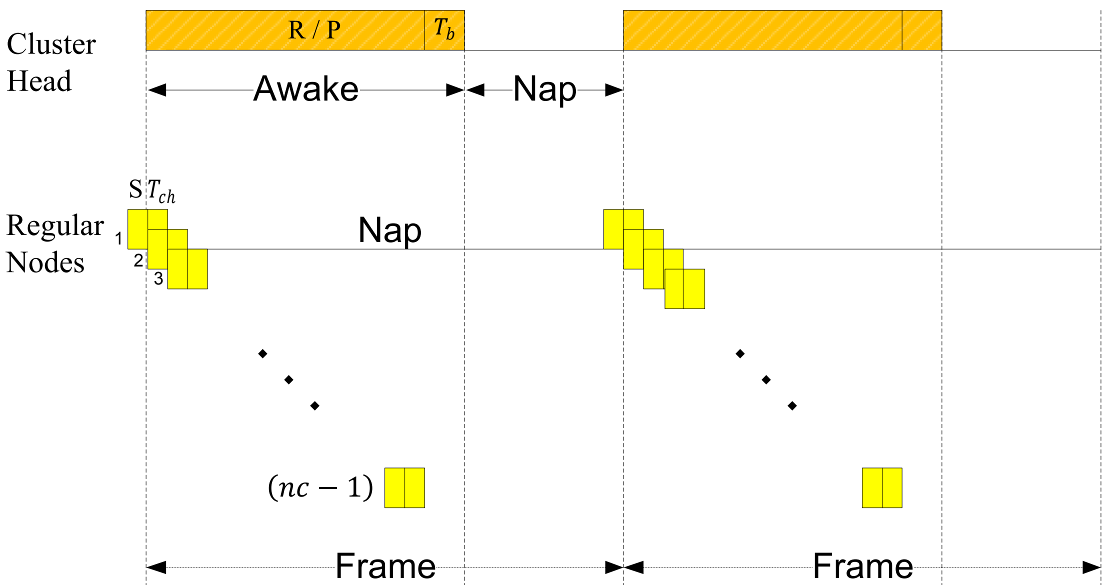


Figure 5.2. Timing of awake and nap intervals for a cluster head and its $(nc-1)$ regular nodes. (Awake periods shown in gray, and Nap periods shown in white.)

In a WSN with N sensor nodes and K_i clusters in Round i, there are N-K_i regular nodes (summed across all clusters) allowed to transmit data to their cluster heads.

Let nc be the number of nodes in the current cluster. Then, the Awake interval of the cluster head should be long enough to accommodate arrival of all messages from $nc-1$ regular nodes of the cluster. Therefore, the average receiving window size for the cluster head must be at least $\tau_{snd}^{Reg} \times (nc - 1)$, where τ_{snd}^{Reg} is the average time that a regular node needs to transmit a message with sensed data to its cluster head (cf. Figure 5.2).

Figure 5.2 shows that each Awake period for cluster heads consists of two major parts: the receiving and processing interval *R/P* (for data from regular nodes), and the transmitting interval T_b (for data sent to the base station). Figure 5.2 also shows that each Awake period for regular nodes consists of two major parts: the sensing interval *S*, and the transmitting interval T_{ch} (for data sent to the cluster head).

To prevent collisions among regular nodes sending data to their cluster heads, the transmission intervals for the regular nodes are carefully scheduled (as shown in Figure 5.2 by non-overlapping T_{ch} intervals for the regular nodes). The last T_{ch} interval for a primary ends soon enough to leave at least time T_b of the Awake period available to the cluster head for data transmission to its base station.

As mentioned earlier, there are two energy-consumption inefficiencies for cluster heads in LEACH. First, there is the *hotspot problem*: due to its extra duties, a cluster head uses more energy than regular sensor nodes. Second, the regular sensor nodes with overlapping target coverages generate redundant data, which creates unnecessary load on cluster heads.

LEACH does not propose a complete solution to either of these problems. It incorporates well-planned rotation of the cluster head role among all nodes in a cluster, and ensures that (with a high probability) all nodes serve as a cluster head only once during WSN lifetime; in this way LEACH tries to even out long-term energy usage by all nodes in a cluster. However, LEACH does not compensate for the loss of energy suffered by a node during its cluster head service.

The well-planned rotation of the cluster head role is the only partial solution for the first problem given in LEACH. LEACH does not give solutions for the second problem.

5.3 Notation

Table 5.1 shows notation used in this research. If values of a variable X are the same in LEACH and LEACH-SM, we use X to denote the variable. Otherwise, we use X to denote the variable in LEACH and $\bar{\bar{X}}$ to denote the variable in LEACH-SM.

Table 5.1. Notation.

Symbol	Description
B_{cap}	Initial battery charge
B^{Setup}	Battery energy consumed during all R cluster setup phases in LEACH/LEACH-SM
B^{CH}	The charge consumed by a cluster head during all frames of a single round
$B^{CH+Reg-rem}$	The remaining battery charge for all cluster head and regular node activities
$B^{Reg-rem}$	The remaining battery charge for all regular node activities
l	Data packet size without header
$l^* - l$	Data packet size without header

Table 5.1 – Continued

b_{rec}^{CH} / $\bar{\bar{b}}_{rec}^{CH}$	Size of data received by a cluster head from a regular node in LEACH/LEACH-SM
d^{CH} / $\bar{\bar{d}}^{CH}$	Duty cycle of a cluster head in LEACH/LEACH-SM
d^{Reg} / $\bar{\bar{d}}^{Reg}$	Duty cycle of a regular node in LEACH/LEACH-SM
F	Number of frames per round in LEACH/LEACH-SM
I^{CH} / $\bar{\bar{I}}^{CH}$	Average current drawn by a cluster head for the Awake interval in LEACH/LEACH-SM
$I_{rcv+log}^{CH}$	Average current drawn by a cluster head for receiving messages from regular nodes in LEACH/LEACH-SM
I_{agg}^{CH}	Average current drawn by a cluster head for storing and aggregation of the received data in LEACH/LEACH-SM
I_{snd}^{CH}	Average current drawn by a cluster head for sending data in LEACH/LEACH-SM
I^{Reg}	Average current drawn by a regular node during the Awake interval in LEACH/LEACH-SM
$I_{sen+log}^{Reg}$	Average current drawn by a regular node for sensing and logging the sensed data in LEACH/LEACH-SM
I_{snd}^{Reg}	Average current drawn by a regular node for sending data in LEACH/LEACH-SM

Table 5.1 – Continued

$\bar{\bar{I}}^{Spare}$	Average current drawn by the spare sensor node duration the Awake interval LEACH-SM
$\bar{\bar{I}}^{ss}$	Average current drawn by nodes during spare selection phase in EACH-SM
K	Number of WSN clusters (and cluster heads)
L / L^C / L^F / $\bar{\bar{L}}$	WSN lifetime for LEACH/LEACH-C/LEACH-F/LEACH-SM
L^{Resi} / ${L^C}^{Resi}$/ ${L^F}^{Resi}$ / $\bar{\bar{L}}^{Resi}$	Residual WSN lifetime for LEACH/LEACH-C/LEACH-F/LEACH-SM
L^{Spare} / $\bar{\bar{L}}^{Resi}_{Spare}$	Lifetime and residual lifetime for a spare in LEACH-SM
N	Number of WSN nodes
nc	Number of nodes in a cluster
R / $\bar{\bar{R}}$	Number of rounds in LEACH/LEACH-SM
r	Average data transmission rate from a regular node to its cluster head or from a cluster head to a base station in LEACH/LEACH-SM
T	Average frame length, that is, the average duration of the Awake interval + the average duration of the Nap interval in LEACH/LEACH-SM
Q^{Setup}	Total charge consumed by the node during all setup phase in LEACH / LEACH-SM

Table 5.1 – Continued

Q^{CH} / $\bar{\bar{Q}}^{CH}$	Total charge consumed by cluster head in LEACH / LEACH-SM
Q^{Reg}	Total charge consumed by regular node in LEACH / LEACH-SM
Q^{Total} / $\bar{\bar{Q}}^{Total}$	Total charge consumed by each node during its lifetime (and WSN lifetime) in LEACH / LEACH-SM
σ^{CH} / $\bar{\bar{\sigma}}^{CH}$	Duration of a Nap interval of a cluster head in LEACH/LEACH-SM
σ^{Reg} / $\bar{\bar{\sigma}}^{Reg}$	Average duration of the Nap interval of a regular node in LEACH/LEACH-SM
τ^{Setup} / $\bar{\bar{\tau}}^{Setup}$	Duration of the setup interval in LEACH/LEACH-SM
I^{Setup}	Average current drawn by a node during setup phase in LEACH/LEACH-SM
α	The ratio of cluster nodes (with the cluster head excluded) that become spares in LEACH-SM
β / $\bar{\bar{\beta}}$	The factor by which data aggregation process reduces data size in LEACH/LEACH-SM
τ^{CH} / $\bar{\bar{\tau}}^{CH}$	Duration of the Awake interval of a cluster head in LEACH/ LEACH-SM
$\tau^{CH}_{rcv+log}$ / $\bar{\bar{\tau}}^{CH}_{rcv+log}$	Time taken by a cluster head for receiving and logging (storing) messages from regular nodes in LEACH/LEACH-SM

Table 5.1 – Continued

τ_{agg}^{CH} / $\bar{\bar{\tau}}_{agg}^{CH}$	Average time taken by a cluster head for aggregation of data received from its regular nodes in LEACH/LEACH-SM
τ_{snd}^{CH} / $\bar{\bar{\tau}}_{snd}^{CH}$	Time taken by a cluster head for sending data to its base station in LEACH/LEACH-SM
τ^{Reg}	Duration of the Awake interval of a regular node in LEACH/LEACH-SM
$\tau_{sen+log}^{Reg}$	Time taken by a regular node in sensing and logging sensed data in LEACH/LEACH-SM
τ_{snd}^{Reg}	Time taken by a regular node for sending data to its cluster head in LEACH/LEACH-SM
$\bar{\bar{\tau}}^{Spare}$	Duration of the Awake interval for a spare node in LEACH-SM
$\bar{\bar{\tau}}^{ss}$	Duration of the spare selection interval in LEACH-SM

5.4 Calculating Duration of Awake Interval for LEACH

In this section, we calculate the duration of Awake intervals for cluster head and regular nodes in the LEACH protocol. Note that, Awake interval is different for each kind of sensor nodes. It depends upon many factors such as data processing, logging rate and data transmission/receiving rate of sensor node and roll of the sensor node. The Awake interval should be long enough to accommodate a single and data bit transmit/receive.

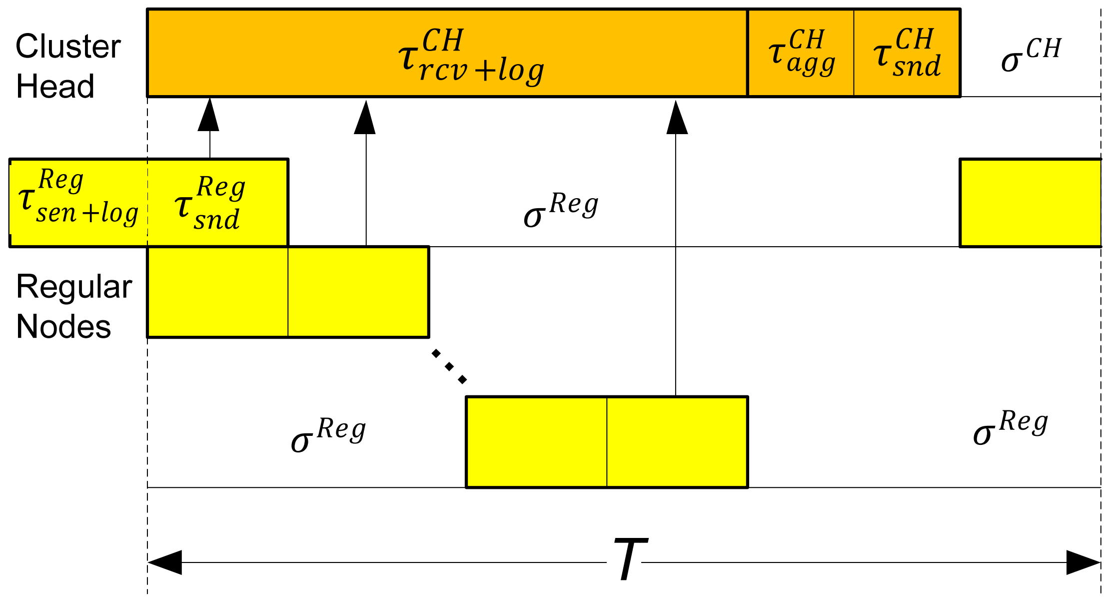


Figure 5.3. Different periods within a frame for a cluster head and regular nodes in LEACH. The arrows from Regular Nodes to Cluster Head denote transmissions of sensed data. *T* is frame duration.

5.4.1 Duration of Awake Interval for Regular Sensor Nodes

Regular sensor nodes collect a certain number of samples (raw data) at a chosen sampling rate from their sensing hardware (onboard sensors) and log (store) the samples into its persistent–storage (EEPROM) [Tin02]. At regular time intervals, regular nodes retrieve data from their storage, and transmit them to their cluster heads.

The length of the Awake interval for a regular node (shown in gray in Figure 5.3) is the sum of the durations for the sensing/logging period $(\tau_{sen+log}^{Reg})$ and the sending period (τ_{snd}^{Reg}). The former depends on the required number of samples and the sampling rate,[7] and the latter depends on the data transmission rate.

[7] The sampling rate is determined by the application using the WSN.

Assuming that the analog sensors of a regular node gather data at up to 1,280 samples per second, and the ADC unit of the node (cf. Figure 2.1) produces 10 bits per sample, the regular node produces 12,800 bits of sensed data per second.

Let the length of a message sent by a regular node to its cluster head be l bits. Then, time taken by a regular node for sensing (and logging) l bits of data is:

$$\tau_{sen+log}^{Reg}(l) = l \,/\, 12{,}800\ [sec] \qquad (5.1)$$

Let the transmission rate from the regular sensor node to the cluster head be *r* bits/sec, and let l' be the total length of the packet headers for the packets constituting the messages (with *l* bits of data). Then, time taken by a regular node for transmitting $l^* = l + l'$ bits of sensed and header data is:

$$\tau_{snd}^{Reg}(l^*, r) = l^*/r\ [sec] \qquad (5.2)$$

The length of the Awake interval for a regular node is:

$$\tau^{Reg}(l, l^*, r) = \tau_{sen+log}^{Reg}(l) + \tau_{snd}^{Reg}(l^*, r)\ [sec] \qquad (5.3)$$

5.4.2 Duration of Awake Interval for Cluster Head

The duration of the Awake interval for cluster heads (shown in gray in Figure 5.3) depends upon: (i) the number of primary nodes within the cluster, and (ii) the data transmission rate for the regular nodes.

Let *nc* be the number of primaries in the current cluster. The *receiving window* for the cluster head is the time taken by the cluster head for receiving and logging messages from all *nc* – 1 regular nodes. The required (minimum) average length of the *receiving window* for a cluster head is:

$\tau_{rcv+log}^{CH}(l^*, nc, r) =$

$=(nc-1)\times\tau_{snd}^{Reg}(l^{*},r)\ [sec]$ (5.4)

Regular nodes with overlapping target coverage generate redundant data. A cluster head is responsible for receiving such redundant data, and aggregating them. Data aggregation techniques eliminate data redundancies, and reduce the number of data packets that the cluster heads sends to its base station [Hein00].

Time taken by a cluster head for data aggregation depends upon the number and size of messages received from regular nodes. Let t_{agg} be the average time taken by the cluster head to aggregate one bit of data ([sec/bit]). The cluster head receives $b_{rec}^{CH}=(nc-1)\times l^{*}$ bits of data (recall that $l*$ is the message length). Hence, time used by a cluster head for data aggregation is:

$$\tau_{agg}^{CH}(l^{*},nc,t_{agg})=t_{agg}\times b_{rec}^{CH}\ [sec]=$$
$$=t_{agg}\times(nc-1)\times l^{*}\ [sec] \quad (5.5)$$

Regular nodes with overlapping target coverages generate redundant data. After receiving all data from regular nodes, the cluster head aggregates received data, reducing data size by a factor of β [%]; $0\leq\beta<100$.

Since the total size of sensed data received by a cluster head is $b_{rec}^{CH}=(nc-1)\times l^{*}$ [bits], then the aggregated data size b_{agg}^{CH} is:

$$b_{agg}^{CH}(\beta,l^{*},nc)=\beta\times(nc-1)\times l^{*}\ [bits] \quad (5.6)$$

The average time τ_{snd}^{CH} taken by the cluster head to forward the aggregated data to its base station at the transmission rate *r* [bits/sec] is:

$$\tau_{snd}^{CH}(\beta,l^{*},nc,r)=b_{agg}^{CH}(\beta,l^{*},nc)/\,r\ [sec]=$$
$$=\beta\times(nc-1)\times l^{*}\,/\,r\ [sec] \quad (5.7)$$

From Equations (5.5), (5.6) and (5.7), the total average time during which the cluster head remains Awake is:

$$\tau^{CH}(\beta, l^*, nc, r, t_{agg}) =$$
$$= \tau^{CH}_{rcv+log}(l^*, nc, r) + \tau^{CH}_{agg}(l^*, nc, t_{agg}) + \tau^{CH}_{snd}(\beta, l^*, nc, r)\ [sec] \tag{5.8}$$

Note that τ^{CH} depends, among others, upon the number of nodes nc in the given cluster.

5.4.3 Duration of Nap Interval for Cluster Head

The Nap interval for a cluster head (cf. Figure 5.3) is:

$$\sigma^{CH}(\beta, l^*, nc, r, t_{agg}, T) = T - \tau^{CH}(\beta, l^*, nc, r, t_{agg})\ [sec] \tag{5.9}$$

where T is the frame length. If a cluster head remains awake continuously, then $\tau^{CH} = T$ and $\sigma^{CH} = 0$; otherwise, $\sigma^{CH} > 0$.

Since τ^{CH} from Equation (5.8) is much larger than τ^{Reg} from Equation (5.3), a cluster head must stay awake for a much longer period than a regular node. This explains why it consumes much more energy than a regular node.

5.5 Calculating Duty Cycle for LEACH

Primary nodes are not always Awake (transmitting or receiving data); they may Nap to save energy whenever they need not be Awake. (So primaries follow cycles of Awake and Nap intervals, as shown in Figure 5.1.)

The *duty cycle* for a node is defined as the ratio of the length of its Awake interval to the frame duration.

The length of the Awake interval for a cluster head depends upon the number of regular nodes within the cluster. This puts a lower limit on the frame length. We cannot set it shorter than the duration of the Awake interval of the busiest cluster head; otherwise, this cluster head would be unable to receive data from all regular nodes within its cluster.

Once we set the frame length (considering the busiest cluster head), the duty cycles for all WSN nodes will be affected. In other words, the duty cycle for each WSN node depends upon the duration of the Awake interval of the busiest cluster head.

In calculating duty cycles for all nodes, we need to look at two cases: (i) when the duration of the Nap interval for the cluster head is zero, and (ii) when the duration of the Nap interval for the cluster head is not zero.

5.5.1 Case 1: Duration of Nap Interval for Cluster Head is Zero

5.5.1.1 Calculating the Duty Cycle for Cluster Head

When the duration of the Nap interval σ^{CH} is zero, a cluster head will remain in the Awake mode continuously, that is, $\tau^{CH} = T$. In this case, the duty cycle for a cluster head is:

$$d^{CH}\left(\beta, l^{*}, nc, r, t_{agg}, T\right) = \tau^{CH}\left(\beta, l^{*}, nc, r, t_{agg}\right) / \mathrm{T} = \mathrm{T}/\mathrm{T} = 100\% \qquad (5.10)$$

5.5.1.2 Calculating the Duty Cycle for Regular Nodes

The duty cycle for a regular node is:

$$d^{Reg}(l, l^{*}, r, T) = \tau^{Reg}(l, l^{*}, r)/T \times 100\% \qquad (5.11)$$

5.5.2 Case 2: Duration of Nap Interval for Cluster Head is Not Zero

5.5.2.1 Calculating the Duty Cycle for Cluster Head

If $\sigma^{CH} > 0$, the duty cycle for a cluster head is:

$$d^{CH}\left(\beta, l^{*}, nc, r, t_{agg}, T\right) =$$

$$= \tau^{CH}\left(\beta, l^{*}, nc, r, t_{agg}\right) / \mathrm{T} = \left(100 - \sigma^{CH}\left(\beta, l^{*}, nc, r, t_{agg}, T\right)\right) \times 100[\%] \qquad (5.12)$$

5.5.2.2 Calculating the Duty Cycle of Regular Nodes

In this case the duty cycle of regular nodes is:

$$d^{Reg}(l, l^{*}, r, T) = \tau^{Reg}(l, l^{*}, r)/T \ \times 100\% \qquad (5.13)$$

5.6 Energy Consumption Model for LEACH

In this section, we show the energy consumption model for LEACH. We focus here on a single WSN sensor node, even though the final goal is calculating WSN lifetime. As was mentioned, we assume that energy, needed for sensing, logging data, and sending/receiving of data [Dress07], is provided by node batteries.

We are using the sensor node model shown in Figure 2.1 (it is more detailed than the model given in Ref. [Hein00]). The sensor node components primarily contributing to the overall energy consumption are: the on board sensors, the analog-to-digital converter unit (ADC), the micro controller, and the communication module (including the sending and receiving modules. Energy consumed in the process of sampling, processing and logging data by a sensor node is comparable to the energy consumed by the sender and receiver circuits of the sensor node. To run all components, the Microcontroller needs be Awake all the time.

Energy consumption by a node includes: (i) energy consumption during sensing and logging (incl. energy consumed by the onboard sensors), (ii) energy consumption during sending and receiving data. (In our analysis we ignore small amounts of energy needed by regular nodes to receive rare and short messages from their cluster heads, and by cluster heads to send these messages to regular nodes.)

Knowing time spent by each node in each state, as well as the current drawn by the node circuitry in each state [Dress07], we can calculate the average energy consumed by each node.

5.6.1 Average Current Drawn by Regular Nodes

Let $I_{sen+log}^{Reg}$ and I_{snd}^{Reg} be the average current used by a regular node during sensing and logging, and the average current used by the node during sending data to its cluster head, respectively. Then, the average current consumed by a regular node during its Awake interval is (all parameter lists omitted):

$$I^{Reg} = \frac{\left(\tau_{sen+\log}^{Reg} \times I_{sen+log}^{Reg}\right) + \left(\tau_{snd}^{Reg} \times I_{snd}^{Reg}\right)}{\tau_{sen+log}^{Reg} + \tau_{snd}^{Reg}} \; [A] \tag{5.14}$$

5.6.2 Average Current Drawn by Cluster Heads

Let $I_{rcv+log}^{CH}$ be the average current drawn by a cluster head during receiving messages from regular nodes, I_{agg}^{CH}—the average current drawn by it during aggregation of received data, and I_{snd}^{CH} —the average current drawn by it during sending data to the base station. Then, the average current drawn by a cluster head during its Awake interval is:

$$I^{CH} = \frac{\left(\tau_{rcv+log}^{CH} \times I_{rcv+log}^{CH}\right) + \left(\tau_{agg}^{CH} \times I_{agg}^{CH}\right) + \left(\tau_{snd}^{CH} \times I_{snd}^{CH}\right)}{\tau_{rcv+log}^{CH} + \tau_{agg}^{CH} + \tau_{snd}^{CH}} [A] \quad (5.15)$$

5.7 Special-case Calculation of WSN Lifetime for LEACH

As is often the case, obtaining a closed formula describing a complex phenomenon is impossible (or, at least, beyond time or capability limitations of the analyzers). Instead, obtaining a closed formula is limited to a special case of the phenomenon, in which simplifying assumptions facilitate obtaining a closed formula.

The results obtained for a special (simplified) case are still very useful. They can be used to validate results of extensive simulations run for the original general case, "described" by the simulation in its full (or at least much more complete) complexity.

Unable to provide a closed formula for determining WSN lifetime in its full complexity, we make simplifying assumptions in this chapter.

Let *N* be the number of all WSN nodes, and *K* be the number of clusters in Round 1. We assume that: (i) *remainder(N/K)* = 0, i.e., *N* is evenly divisible by *K*; (ii) the number of clusters in *each* round is *K*, (iii) all clusters are of size *R* = *N/K* (recall that R is the number of rounds); as a consequence, duration of all frames for all rounds is identical (because during each frame the same number of regular nodes need to send sensed data to their cluster heads); (iv) in each round LEACH finds a good cluster node; that is, in each round LEACH finds an appropriate node that did not serve as a cluster head in previous rounds; and (v) the number of frames *F* per round is constant (recall that *F* is the optimization parameter that allows to maximize WSN lifetime); and (vi) no current is drawn by nodes during their Nap intervals.

As a consequence of Assumption (iii), we will have R rounds during WSN lifetime. The simplest way of realizing Assumption (iv) is by using the cluster configuration created in Round 1 in all remaining rounds as well. Assumptions (iii) and (iv) assure that each node plays the cluster head role only once.

Before providing a closed formula for determining WSN lifetime, we first calculate the number *F* of frames per round (an optimization parameter for WSN lifetime in LEACH). *F* needs be calculated before we can calculate WSN lifetime. Finding *F* is the most complex part of finding WSN lifetime *L*.

Theorem 1: Let B_{cap} $[Ah]$be the initial battery charge; I^{CH} —the average current drawn by the cluster head (more precisely, by a node playing the role of a cluster head) during its Awake interval; I^{Reg} —the average current drawn by a regular node (more precisely, a node playing the role of a regular node) during its Awake interval; I^{Setup}— the average current drawn by a node during the cluster setup phase; R —the number of rounds; τ^{CH} and τ^{Reg} —the durations of the Awake intervals for a regular node and a cluster head, respectively; and τ^{Setup} —the duration of the setup phase. Then the number of frames *F* per round in LEACH is:

$$F = \left\lfloor \frac{3600 \times B_{cap}[Ah] - (I^{Setup} \times \tau^{Setup} \times R)}{(I^{CH} \times \tau^{CH}) + I^{Reg} \times \tau^{Reg} \times (R-1)} \right\rfloor \tag{5.16}$$

Proof: With *N* and *K* being the number of all WSN nodes and the number of clusters in each round, the total number of rounds is *R* = *N/K* (where, as assumed, *reminder(N/K)* = 0). By our assumptions, R is also equal to the number of nodes in each cluster.

According to LEACH, each primary will be a cluster head exactly once in its lifetime. This means that it will be a regular node for $(R-1)$ rounds.

The following consideration will be easier to follow when looking at Figure 5.1.

During the setup phase, the node consumes the charge equal to $I^{Setup} \times \tau^{Setup}$. Since the phase is repeated in each round, the total charge consumed by the node during all setup phase is:

$$Q^{Setup} = (I^{Setup} \times \tau^{Setup} \times R)/3600 \text{ [Ah]} \tag{5.17}$$

Since a node plays the cluster head role in exactly *F* frames of one round during WSN lifetime, the charge it consumes during its entire cluster head service during WSN lifetime is:

$$Q^{CH} = (\, I^{CH} \times \tau^{CH} \times F\,)/3600\ [Ah] \tag{5.18}$$

Since a node plays the regular node role in exactly *F* frames of *R*-1 rounds during WSN lifetime, the charge it consumes during its entire regular node service during WSN lifetime is:

$$Q^{Reg} = I^{Reg} \times \tau^{Reg} \times F \times (R-1)/3600\ [Ah] \tag{5.19}$$

Hence, the total charge consumed by each node during its lifetime (and WSN lifetime) is:

$$Q^{Total} = Q^{Setup} + Q^{CH} + Q^{Reg} =$$

$$[(I^{Setup} \times \tau^{Setup} \times R) + (I^{CH} \times \tau^{CH} \times F) + \{\, I^{Reg} \times \tau^{Reg} \times F \times (R-1)\}]/3600\ [Ah]$$

If the node uses all energy available to it from its battery (its full initial charge B_{cap}), then $Q^{Total}[Ah] = B_{cap}[Ah]$. Hence:

$$[(I^{Setup} \times \tau^{Setup} \times R) + (I^{CH} \times \tau^{CH} \times F) + \{ I^{Reg} \times \tau^{Reg} \times F \times (R-1)\}]$$

$$/3600\ [Ah] = B_{cap}\ [Ah]$$

$$F = \left\lfloor \frac{3600 \times B_{cap} - (I^{Setup} \times \tau^{Setup} \times R)}{(I^{CH} \times \tau^{CH}) + I^{Reg} \times \tau^{Reg} \times (R-1)} \right\rfloor \tag{5.20}$$

Q.E.D.

Theorem 2: Let d^{CH} and d^{Reg} be duty cycles for cluster heads and regular nodes, respectively; *F*—the number of frames per round; *R*—the number of rounds during the entire WSN lifetime; τ^{Setup}—the duration of the setup phase; *T*—the duration of each frame; and the remaining symbols—as defined in Theorem 1. Then, WSN lifetime *L* for LEACH is:

$$L = \frac{\tau^{CH} \times F}{d^{CH}} + \frac{3600 \times B_{cap} - (I^{Setup} \times \tau^{Setup} \times R) - (I^{CH} \times \tau^{CH} \times F)}{I^{Reg} \times d^{Reg}} \tag{5.21}$$

Proof: A setup overhead is paid only once, at the beginning of the each round. If $B_{cap}$is the initial battery charge and B^{Setup} is the battery energy consumed during all *R* cluster setup phases, then:

$$B^{Setup} = I^{Setup} \times \tau^{Setup} \times R \tag{5.22}$$

The energy remaining for all node activities other than cluster setup (i.e. for cluster head and regular node activities) is:

$$B^{CH+Reg-rem} = B_{cap} - B^{Setup} = B_{cap} - (I^{Setup} \times \tau^{Setup} \times R) \tag{5.23}$$

In its lifetime, each primary node serves as a cluster head only once during a single round. The charge consumed by a cluster head during all frames of that single round is: $B^{CH} = I^{CH} \times \tau^{CH} \times F$.

The remaining battery charge for all regular node activities (during all frames in R-1 rounds) is:

$$B^{Reg-rem} = B^{CH+Reg-rem} - B^{CH}$$

$$= [\, B_{cap} - (I^{Setup} \times \tau^{Setup} \times R)] - (I^{CH} \times \tau^{CH} \times F)$$

This charge is fully consumed by the node during all its regular-node activities (in all frames of R-1 rounds). Therefore, the charge consumed by a node during its regular-node activities is: $B^{Reg} = B^{Reg-rem}$.

The WSN lifetime L in LEACH is approximately equal to the lifetime of any primary node (since LEACH tries to assure that all nodes die at the same time). The latter consist of the node's lifetime L^{CH} as a cluster head plus the node's lifetime L^{Reg} as a regular node. Hence, WSN lifetime L is:

$$L = L^{CH} + L^{Reg} = \frac{B^{CH}}{I^{CH} \times d^{CH}} + \frac{B^{Reg}}{I^{Reg} \times d^{Reg}}$$

$$= \frac{I^{CH} \times \tau^{CH} \times F}{I^{CH} \times d^{CH}} + \frac{[\, B_{cap} - \left(I^{Setup} \times \tau^{Setup} \times R\right)] - (I^{CH} \times \tau^{CH} \times F)}{I^{Reg} \times d^{Reg}}$$

Thus:

$$L = \frac{\tau^{CH} \times F}{d^{CH}} + \frac{B_{cap} - (I^{Setup} \times \tau^{Setup} \times R) - I^{CH} \times \tau^{CH} \times F}{I^{Reg} \times d^{Reg}} \qquad (5.24)$$

Q.E.D.

5.8 Calculating WSN Lifetime for LEACH-C and LEACH-F

Two main variants of LEACH are LEACH-C (LEACH-Centralized) and LEACH-F (Fixed Cluster, Rotating Cluster-Head).

As stated above, LEACH incorporates well-planned rotation of the cluster head role, as well as adaptive self-configuration cluster formation in each round (cf. Figure 5.1). LEACH-C differs from LEACH only by using a *centralized* control algorithm to form better clusters. Therefore, we can use Theorem 2 to calculate WSN lifetime for LEACH-C:

$$L^{C} = L$$

In contrast to LEACH, LEACH-F forms clusters only once at the beginning of Round 1 (then, for each round, new cluster heads are selected within the *fixed* clusters). Therefore, a setup overhead is paid only once. Thus, we can get WSN lifetime L^F for LEACH-F by replacing R in Theorem 2 with the value 1. Then, WSN lifetime L^F for LEACH-F is:

$$L^{F} = \frac{F \times \tau^{CH}}{d^{CH}} + \frac{B_{cap} - (I^{Setup} \times \tau^{Setup}) - (I^{CH} \times F \times \tau^{CH})}{I^{Reg} \times d^{Reg}} \tag{5.25}$$

5.9 Residual WSN Lifetime for LEACH and its Variants

The *residual WSN lifetime at time t* is defined as the remaining life expectancy for the WSN, given that WSN is alive at time *t*. A residual lifetime assessment helps in identification of sensor nodes with low energy resources.

The residual WSN lifetime for LEACH and LEACH-C at any time t is:

$$L^{Resi}\Big|_t = L^{C^{Resi}}\Big|_t = L - t \; 0 \leq \; t \leq L \tag{5.26}$$

Similarly, the residual WSN lifetime for LEACH-F at any time t is:

$$L^{F^{Resi}}\Big|_t = L^F - t \; 0 \leq \; t \leq L^F \tag{5.27}$$

6. LEACH-SM – THE PROPOSED SOLUTION TO THE LEACH INEFFICIENCY PROBLEM

6.1 Cluster Setup Phase of LEACH-SM

LEACH-SM starts with the *cluster setup* phase (cf. Figure 6.1). During this setup phase sensor nodes organize themselves into local clusters, with one node in each cluster selected as the cluster head.

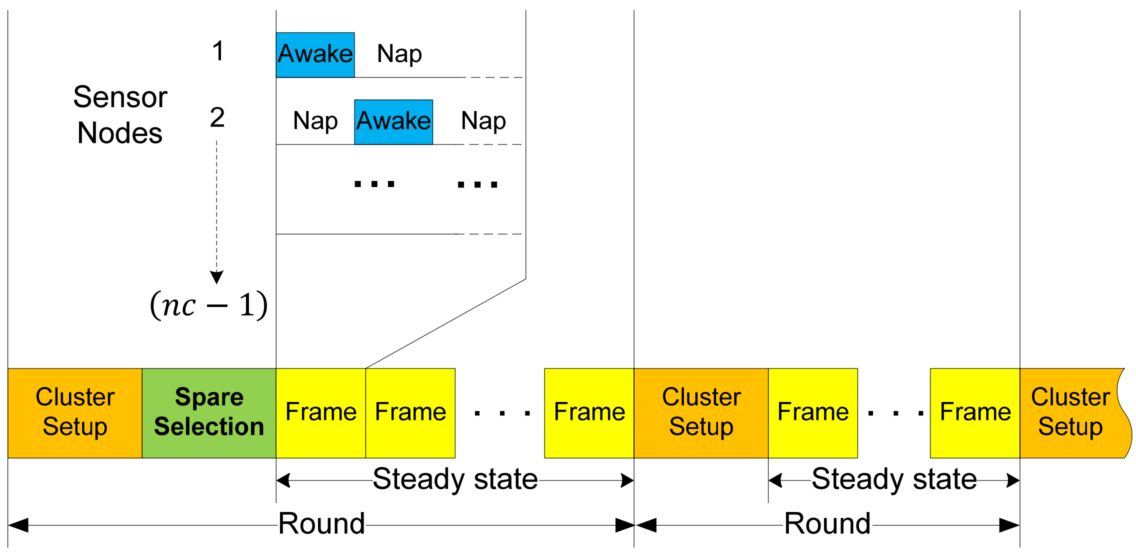


Figure 6.1. Rounds, phases, and frames for LEACH-SM, including the added spare selection phase. Note that spare selection is done only once in WSN lifetime.

Each regular node (a node that is not a cluster head) knows its cluster head and the *received signal strength* RSS_{CH} of the advertisement messages from the cluster head.

6.2 Spare Selection Phase of LEACH-SM

The *spare selection* phase (cf. Figure 6.1) consists of two intervals: the sensing range neighbor discovery interval, and the interval during which DESST (Decentralized Energy-efficient Spare Selection Technique) is run (to increase wireless sensor network lifetime).

6.2.1 Interval 1: Sensing Range Neighbor Discovery

During the *sensing range neighbor* (*SR-neighbor*) *discovery* interval each regular sensor node s discovers its *sensing-range neighbors* (*SR-neighbors*) in the following way. First, node s broadcasts a `hello` message, which is received by all nodes within its sensing range (we assume realistically that the transmission range exceeds the sensing range of a node). The `hello` message contains ID of the sender node s and IDs of the static targets (ID_{tar}) covered by s.

The recipient r of the `hello` message replies with the `hello-reply` message sent back to s. The `hello-reply` message contains ID of its sender r, r's cluster ID, r's RSS_{CH}, and IDs of the static targets (ID_{tar}) covered by r.

Upon receipt of the `hello-reply` message from r, node s stores information brought by the message (i.e., ID, cluster ID, RSS_{CH}, ID_{tar}) in s's SRN table. *SRN table* is a local database of information about SR-neighbors of the node.

Using target information ID_{tar} received in the `hello-reply` message from r, node s can quickly find out if r received the s's `hello` message but does not cover any targets covered by s. In this way s identifies all and only nodes that have sensing ranges overlapping with its own sensing range, that is, nodes that are s's SR-neighbors.

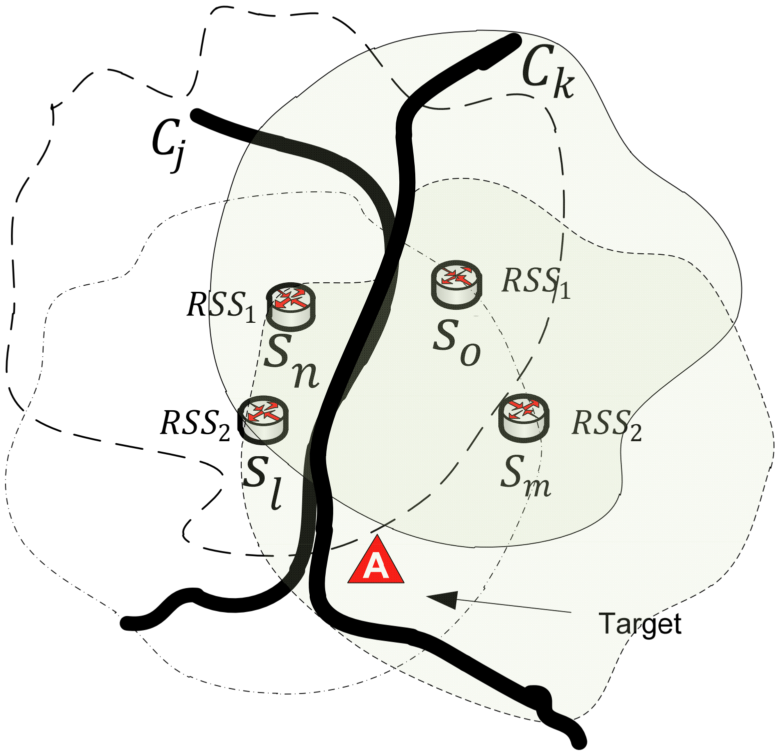


Figure 6.2. Illustration for SR-neighbor discovery.

Let us consider an example shown in Figure 6.2. The sensor nodes s_l and s_n are in the cluster with cluster head C_j, and nodes s_m and s_o are in the cluster with cluster head C_k. The sensor nodes s_l, s_m, s_n and s_o have received signal strengths RSS_2, RSS_2, RSS_1, *and* RSS_1, respectively, where $RSS_1 > RSS_2$. The sensor nodes s_l, s_n are in cluster C_j and the nodes s_m, s_o are in cluster C_k. (The cluster heads for clusters C_k and C_j are not shown in the Figure 6.2.) Target A is covered by s_l and s_m. All four nodes are SR-neighbors for each other.

After the `hello/hello-reply` message exchange is completed by all pairs of the four nodes, their SRN tables look as shown in Figure 6.3 (to avoid clutter, ID_{tar} entries are not shown).

s_l			s_m			s_n			s_o		
ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}
s_n	C_j	RSS_1	s_o	C_k	RSS_1	s_n	C_j	RSS_1	s_o	C_k	RSS_1
s_l	C_j	RSS_2	s_m	C_k	RSS_2	s_l	C_j	RSS_2	s_m	C_k	RSS_2
s_o	C_k	RSS_1	s_n	C_j	RSS_1	s_o	C_k	RSS_1	s_n	C_j	RSS_1
s_m	C_k	RSS_2	s_l	C_j	RSS_2	s_m	C_k	RSS_2	s_l	C_j	RSS_2

Figure 6.3. The SNR tables for four nodes after the `hello—hello-reply` message exchanges by them.

Recall that: $SRN(s_m)$ as the set of all SR-neighbors of s_m. That is:

$$SRN(s_m) = \{ s_p : \ s_p \in SRN(s_m) \} \tag{6.1}$$

Let s_m be a node from cluster C_j. Then, the set of all SR-neighbors of s_m from C_j, denoted by $SRN(s_m, C_j)$, is:

$$SRN(s_m , C_j) = \{ s_p: s_p \in SRN(s_m) \wedge s_p \in C_j \} \tag{6.2}$$

The set of all SR-neighbors of s_l can be expressed as:

$$SRN(s_m) = \bigcup_{j \in \{1,2,3,\dots,N\}} (s_m, C_j) \tag{6.3}$$

Recall that $SRN^{-}(s_m)$ is the set of all SR-neighbors of s_m excluding s_m itself, that is:

$$SRN^{-}(s_m) = SRN(s_m) - \{s_m\} \tag{6.4}$$

For each $s_l \in SRN(s_m, C_j)$ there exists $TS(s_l)$—the *set of targets covered by node* s_l. E.g., if targets A, B and C are covered by sensor node s_l, then $TS(s_l) = \{A, B, C\}$.

6.2.2 Interval 2: Running the Decentralized Energy-efficient Spare Selection Technique (DESST)

DESST is a part of the spare management that allows (in parallel across all clusters) each regular sensor node to select being a primary node or a spare as shown in Figure 6.4. The former enter the *active* power mode (they will be awake or napping at the moment when the spare selection phase ends—cf. Figure 6.1). The latter enter the *passive* power mode (they will be Asleep at the moment when the spare selection phase ends). At the same time, the above-threshold target coverage is assured.

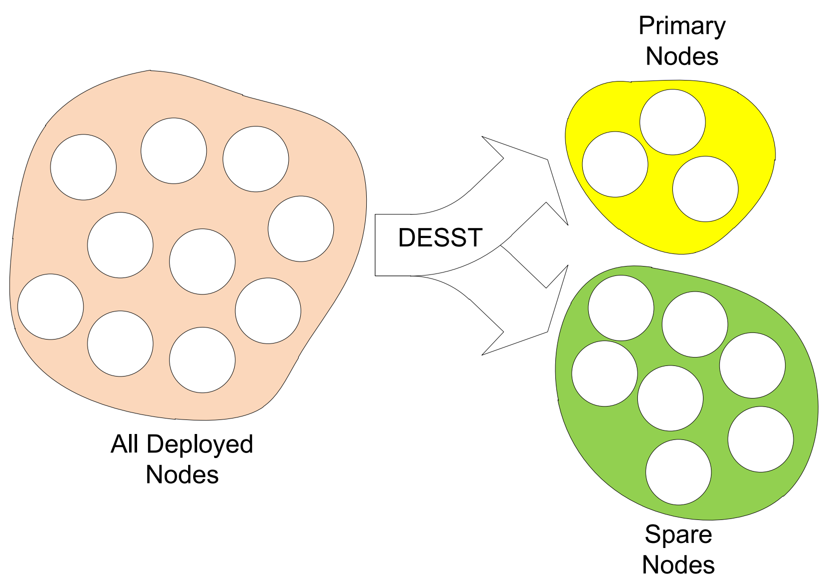


Figure 6.4. DESST puts each WSN node into either passive or active power mode. The former become regular (primary) sensor nodes, and the latter—spare sensor nodes.

Sensing targets can cross cluster boundaries (clusters “limit” transmission of sensing data to the appropriate cluster heads). Due to this fact, we are facing potential race conditions and deadlocks

A *race condition* occurs in DESST when multiple sensor nodes (from the same or different clusters) attempts to decide in parallel whether they should become primaries or spares.

Consider a situation when target *A* is covered only by two nodes s_l and s_m, that belong to clusters C_j and C_K, respectively (as shown in Figure 6.2. Suppose that s_l decides that it is redundant (since it knows that target *A* is covered by its SR-neighbor s_m), and decides to become a spare. In parallel, s_m decides that it is redundant (since it knows that target *A* is covered by its SR-neighbor s_l), and decides to become a spare. As a result of this race condition, target *A* will not be covered at all.

A *deadlock* in DESST occurs when two or more sensor nodes are waiting for each other before making their primary/spare decision. As a simple deadlock example consider two sensor nodes s_l, s_k from the same or different clusters. It is possible that s_l waits for the decision of s_k to make its primary/spare decision, and at the same time s_k waits for s_l .

Algorithm 1: Finding the order in which the nodes from $SRN(l)$ make their primary/spare decisions

```
for each node l do
 sort SRN(l) elements in the increasing order
   of their RSS_CH signal
if there are groups of nodes tied w.r.t. their
RSS_CH value
then sort each such group on the value of ID

// SRN(l)    is now sorted in the order in which l
// and its SR-neighbors make primary/spare
// decision.

node l finds its position p in this ordering
// This means that node l has to wait with its
// decision after p-1 other nodes from SRN(l)
// make their decision.
```

Figure 6.5. Pseudocode of Algorithm 1 in DESST.

DESST allows all regular sensor nodes to make their primary/spare decisions in parallel across all cluster boundaries. It consists of two parts—finding the order of nodes for making the primary/spare decision; and actually making the primary/spare decision. They are discussed next in subsections (a) and (b), respectively.

6.2.2.1 Finding the Order of Nodes for Making the Primary/Spare Decision

This section presents the algorithm that finds the proper order in which nodes from the set $SRN(s_l)$ must make their primary/spare decisions.

In this algorithm design we were looking for the following features: (i) fast convergence; (ii) parallel execution in each cluster; and (iii) resolving race conditions and deadlocks.

Algorithm 1 of DESST, shown in

Figure 6.5, consists of two steps to find the order in which the nodes should make their primary/spare decisions.

Step 1: Ordering sensor nodes by their RSS_{CH} *value*

Sensor nodes with weaker RSS_{CH} signals from their cluster head would spend more energy in communicating with the cluster head than the nodes with stronger RSS_{CH} signals. Therefore, given the set $SRN(s_l)$, the node with the *weakest* signal should be the *first* to make the primary/spare decision, the node with the *second* weakest signals should be the *second* to make the primary/spare decision, etc.

To order the nodes, all nodes (across all clusters) sort records in their SRN tables in the increasing order of RSS_{CH}.

Continuing the example from Figure 6.3, after this step, the SRN tables for nodes s_l, s_m, s_n and s_o will be as shown in Figure 6.6. Note that the SRN tables for all sensor nodes are identical. This is because all four nodes are SR-neighbors of each other.

s_l			s_m			s_n			s_o		
ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}
s_n	C_j	RSS_1	s_n	C_j	RSS_1	s_n	C_j	RSS_1	s_n	C_j	RSS_1
s_o	C_k	RSS_1	s_o	C_k	RSS_1	s_o	C_k	RSS_1	s_o	C_k	RSS_1
s_l	C_j	RSS_2	s_l	C_j	RSS_2	s_l	C_j	RSS_2	s_l	C_j	RSS_2
s_m	C_k	RSS_2	s_m	C_k	RSS_2	s_m	C_k	RSS_2	s_m	C_k	RSS_2

Figure 6.6. The SRN tables for s_l, s_m, s_n and s_o after applying Algorithm 1.

Step 2: Using node ID as a tiebreaker

Without a loss of generality, we assume that each deployed sensor node has a unique ID. In cases when multiple nodes in $SRN(\ s_l\ )$ (a SRN table kept by a given node s_l) have the same RSS_{CH} value, we have a tie. We use node ID as a tiebreaker, which results in finding a total order of nodes in $SRN(\ s_l\ )$.

Recall that in general $SRN(\ s_l\ )$ includes nodes from many clusters. However, node IDs are unique across clusters, so the tiebreaker works also for nodes from different clusters.

After applying Algorithm 1, the SRN tables for s_l, s_m, s_n and s_o are shown in Figure 6.7. Note that the SRN tables for all sensor nodes are identical. This is because in this example all are SR-neighbors of each other.

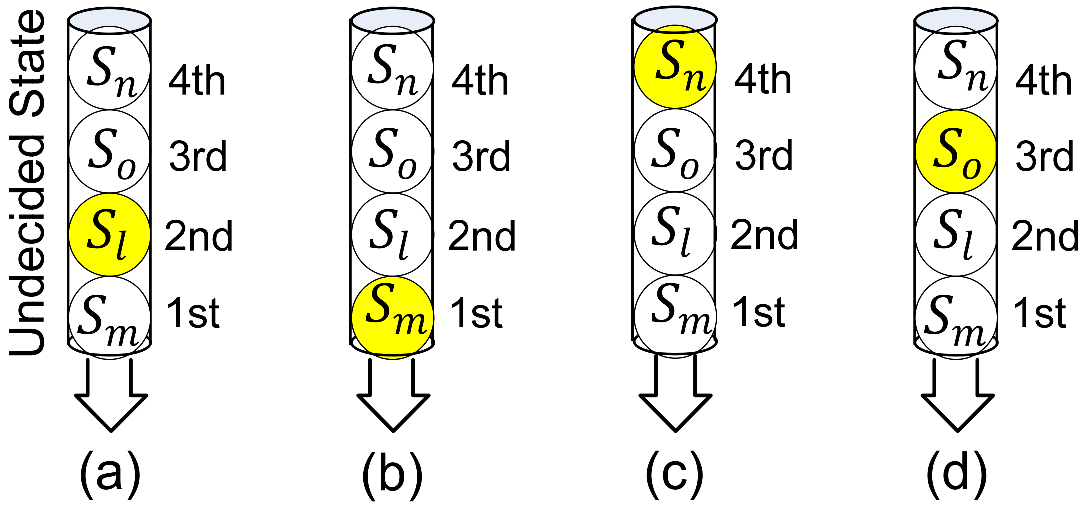


Figure 6.7. The order in which nodes s_l, s_m, s_n and s_o must make the spare/primary decision.

Let us examine the SRN table of one node in detail. In Figure 6.7, both s_m and s_l have the same RSS. In this case we use node ID as a tiebreaker. Since l precedes m in the lexicographical order, s_m wins the tiebreaker and decides its mode sooner. Once s_m does so, s_l can take its turn.

In next section, after finding the candidate position for the deployed sensor nodes, we show the algorithm for efficient scheduling and management of deployed sensor nodes. Our algorithm puts each wireless sensor network node into either passive or active power mode. The former become primary sensor nodes, and the later – spare sensor nodes. This algorithm also envisages how each sensor node decides its power state in parallel in each cluster.

In Figure 6.2, nodes s_l and s_n from cluster C_j and nodes s_m and s_o from cluster C_k have the received signal strengths RSS_2, RSS_1, RSS_2, and RSS_1, resp., where RSS_1 >

RSS_2 (the cluster heads for C_k and C_j are not shown in Figure 6.2 to avoid clutter). Suppose that target A is covered only by s_l and s_m. Also, assume that all four nodes are SR-neighbors for each other. The nodes with the weakest received signal strengths are s_l and s_m . Since the ID *l* precedes the ID m lexicographically, node s_l will be the first to make the primary/spare decision, and node s_m will be the second to make the primary/spare decision. The tiebreaker among s_n and s_o is resolved similarly.

Algorithm 2: Primary/spare Decision

---

for each node s_i **do**
  find $SRN^{-}(s_i)$

if $\cup\{TS(s_l), TS(s_m), TS(s_n), TS(s_o)\} = TS(s_i)$
// if others cover all targets covered by s_i
  then
s_i becomes a spare (passive)
  else
    s_i becomes a primary (active)

Figure 6.8. Pseudocode of Algorithm 2 in DESST.

6.2.2.2 Primary/Spare Decision

Target coverage is one of the most fundamental issues in WSN. Maintaining the required target coverage while reducing the number of sensor nodes is a challenge. A sensor node may decide to become a spare only if the targets covered by it are all collectively covered by its SR-neighbors. Otherwise, some targets become uncovered, resulting in WSN coverage holes. The identification of the coverage holes is not simple and requires extensive investigation

Once the nodes know the order in which they may make their primary/spare decisions, Algorithm 2 of DESST (Figure 6.8) allows them to make proper primary/spare decisions.

Node s decides to become a spare (passive) only if *all* targets covered by s are redundantly covered by its SR-neighbors (otherwise, some targets would become uncovered).

Let us illustrate the algorithm. The sensor node s_l is the first to make its primary/spare decision (cf. Figure 6.6). First, s_l is trying to find out whether $SRN^{-}(s_l)$ are covering the targets that are covered by s_l or not.

In Figure 6.2, targets covered by s_l, s_m, s_n and s_o are:

$TS(s_l) = \{A\}$

$TS(s_m) = \{A\}$

$TS(s_n) = \emptyset$

$TS(s_o) = \emptyset.$

Note that $SRN^{-}(s_l) = \{s_m, s_n, s_o\}$. Then we get:

$$\bigcup\{TS(s_l), TS(s_m), TS(s_n), TS(s_o)\} = \{A\} \qquad (6.5)$$

The union gives the set of all targets covered by $SRN^{-}(s_l)$, so s_l knows what targets are covered by $SRN^{-}(s_l)$. Now, s_l takes the intersection of the union with the set of targets that it covers:

$$\cup\{TS(s_l), TS(s_m), TS(s_n), TS(s_o)\} \cap TS(s_l) \quad (6.6)$$

This intersection tells s_l whether all its targets are covered by its neighbors from $SRN^{-}(s_l)$. There are two cases here:

Case 1: All targets of s_l are covered by $SRN^{-}(s_l)$

$$\{\cup\{TS(s_l), TS(s_m), TS(s_n), TS(s_o)\} \cap TS(s_l)\} = TS(s_l) \quad (6.7)$$

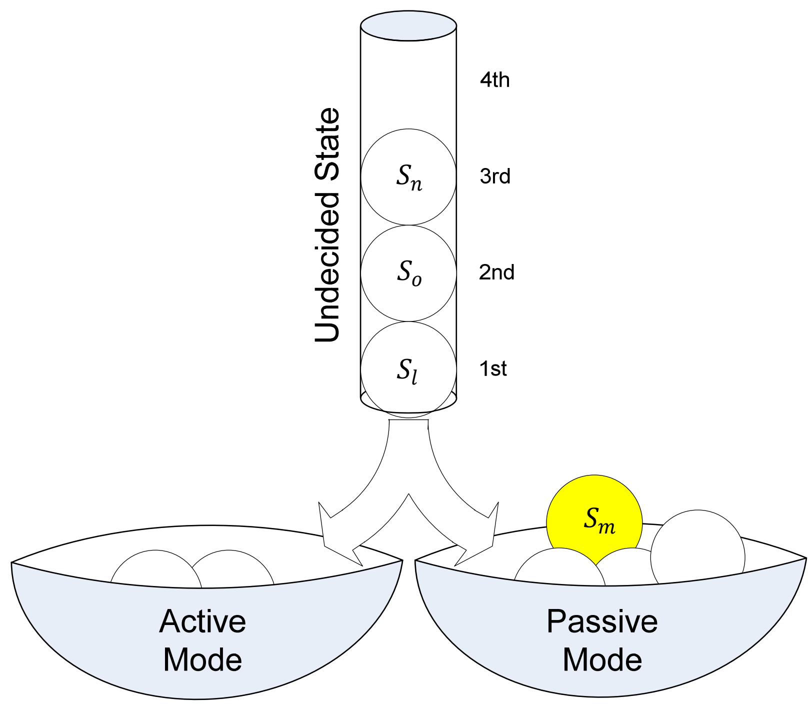


Figure 6.9. The node s_m becomes a spare and switched into passive mode, estimated by DESST during the spare selection phase.

In this case, s_l should become a spare as shown in Figure 6.9. Before becoming a spare (passive) and going Asleep, s_l transmits its decision to all members of the neighbor set $SRN^{-}(s_l)$. After receiving the decision message from s_l, all its SR-neighbors from $SRN^{-}(s_l)$ update their SRN tables and mark s_l as a spare. Next they delete entry for s_l from their SRN tables (because s_l no longer covers any targets).

Note that the spares are awakened when the probability that any primary node exhausted its energy reaches a predefined value.

Case 2: Some targets of s_l are not covered by $SRN^{-}(s_l)$

Since neighbors of s_l from $SRN^{-}(s_l)$ are unable to cover all targets of s_l, s_m must become a primary node (active) as shown in Figure 6.10. As before, s_l broadcasts a message to these neighbors to inform them about making of their primary/spare decision. Now, the next sensor node can start making its primary/spare decision.

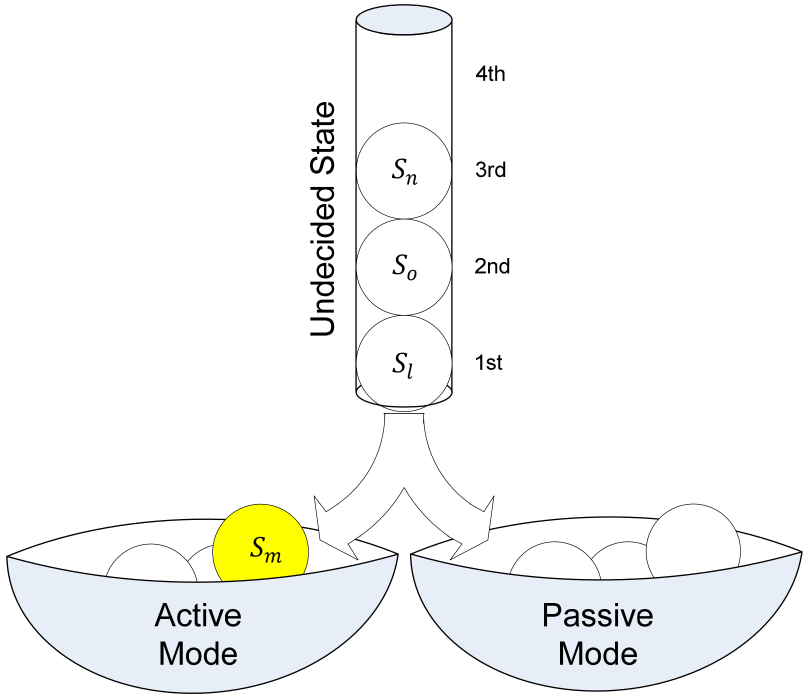


Figure 6.10. The node s_m becomes a primary and switched into active mode, estimated by DESST during the spare selection phase.

WSN is vulnerable to various kinds of network problems. For example the `hello` message could be lost due to collisions, or a malicious sensor node could flood WSN with `hello` messages to break the security of a wireless sensor node (a `hello` flood attack on a node). We assume the presence of an appropriate mechanism to prevent such attacks on WSNs.

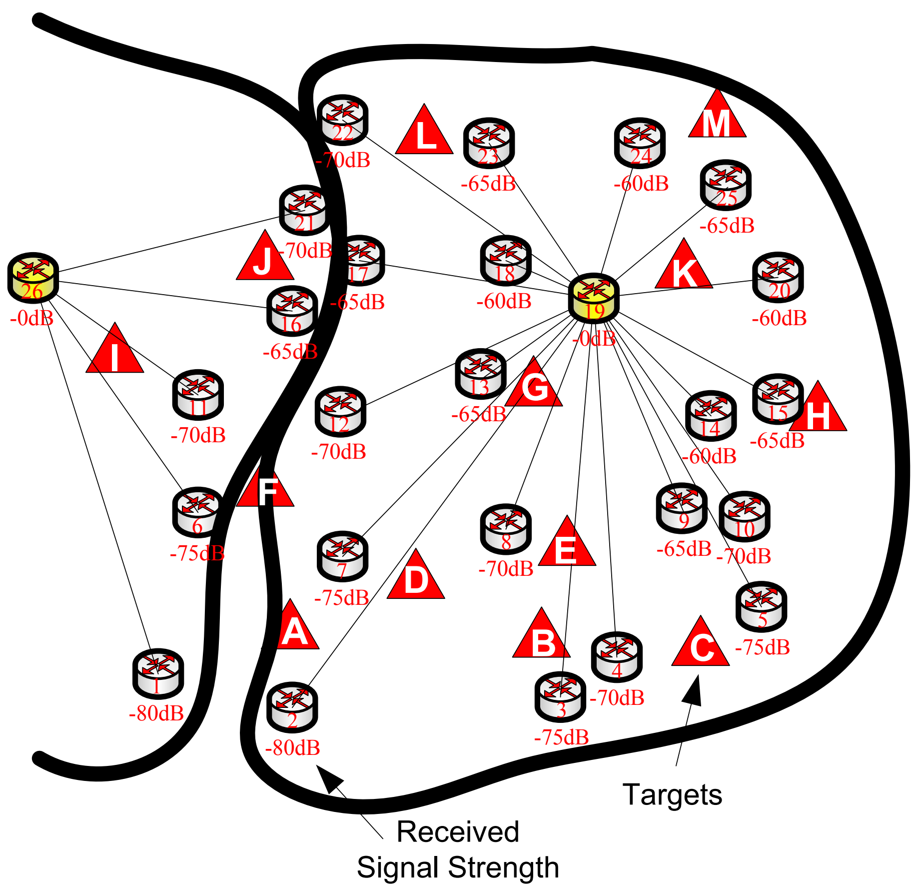


Figure 6.11. Illustration for Example 1 of SR-neighbor discovery.

6.2.2.3 Example 1: SR-neighbor Discovery (Output of Algorithm 1)

Let us consider 26 sensor nodes randomly deployed in an irregular shaped geographical region R with high density. Due to high deployment density there is very high probability that each static target will be covered by more than one sensor nodes.

During the setup phase clusters are created and each regular sensor node knows its cluster head and the distance from it based on the received signal strength RSS_{CH}.

Assume that— as shown in Figure 6.11—sensor nodes s_{19} and s_{26} are cluster heads; sensor nodes s_1, s_6, s_{11}, s_{16} and s_{21} belong to cluster C_{26}, the remaining nodes belong to the cluster head C_{19}; the and triangles labeled A – M represents targets.

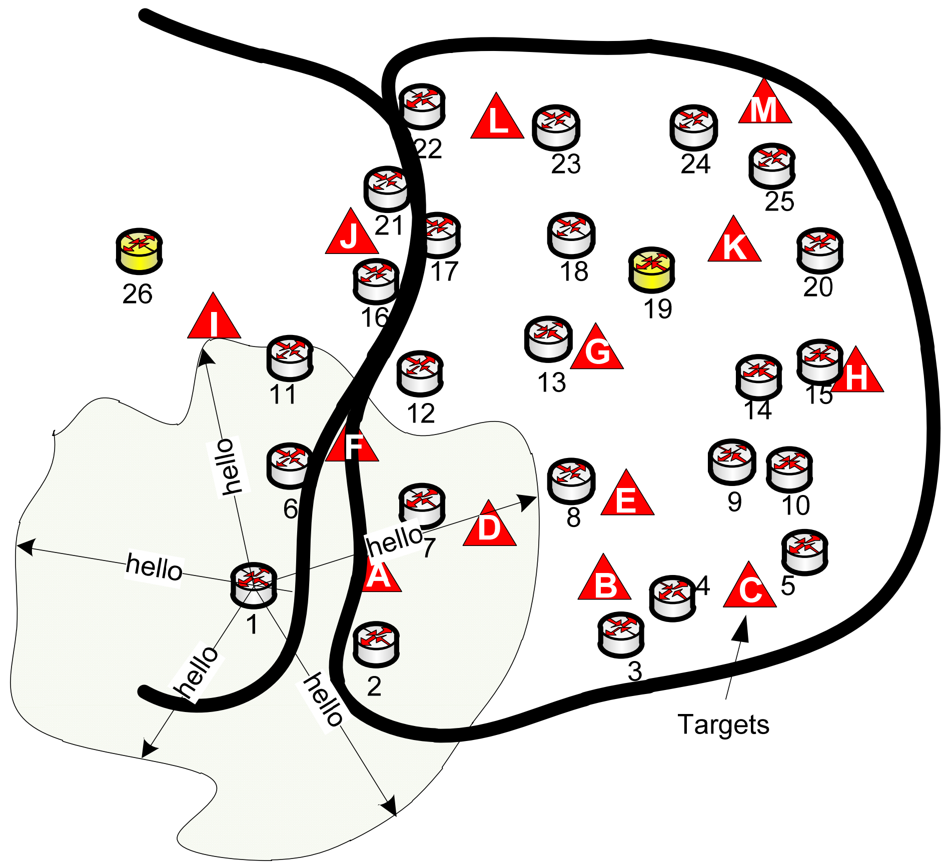
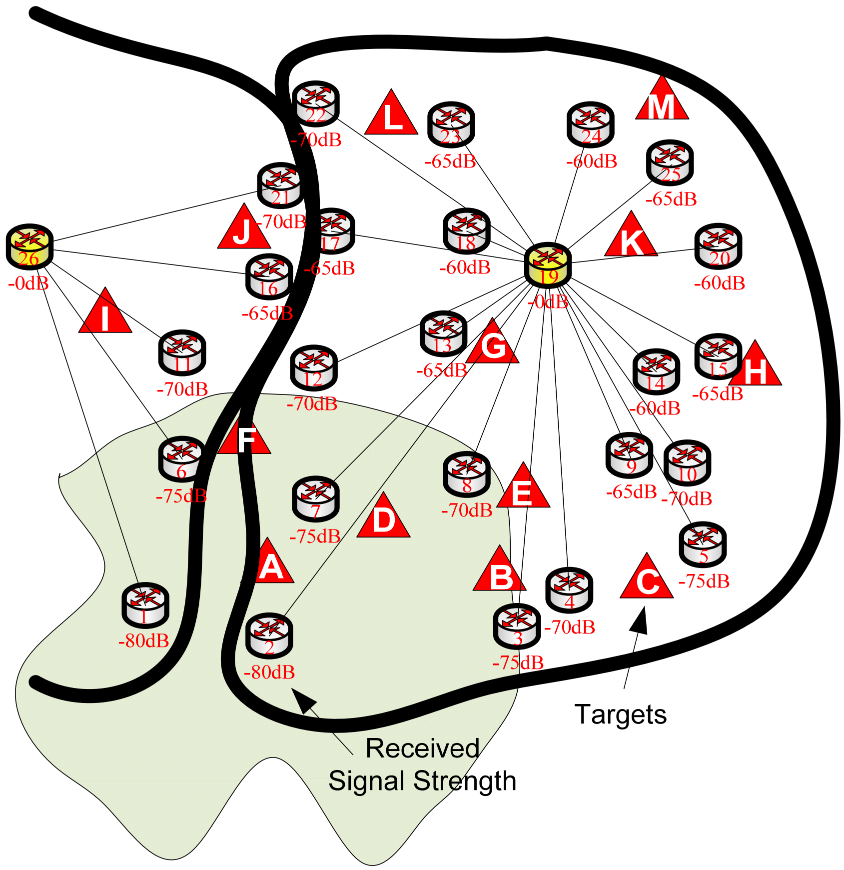


Figure 6.12. Illustration of sending and receiving of a `hello` message.

Suppose that sensor nodes s_1 broadcast the `hello` messages within its sensing range. The sensor nodes s_2, s_6, s_7 and s_{11} receive this broadcast `hello` message coming from node s_{01} (cf. Figure 6.12).



S_2			
ID	C_{ID}	RSS_{CH}	ID_{tar}
s_{01}	C_{26}	-80	$\{A, D, F\}$
s_{02}	C_{19}	-80	$\{A, B, D, E, F\}$
s_{06}	C_{26}	-75	$\{A, D, F, I, J\}$
s_{07}	C_{19}	-75	$\{A, B, D, E, F, G\}$
s_{11}	C_{26}	-70	$\{A, F, I, J\}$

Figure 6.13. SRN table for node 2 (below target A).

After receiving the `hello-reply` messages from sensor nodes s_2, s_6, s_7 and s_{11}, node s_1 stores the received information in its local SRN table, as shown in Figure 6.13.

In this way, sensor node s_{01} discovered that sensor nodes s_2, s_6, s_7 and s_{11} are its SR-neighbors.

After applying the algorithm (cf. Figure 6.5), the SRN tables for all nodes are as shown in Figure 6.14.

S_1			S_2			S_3			S_4			S_5		
ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}
11	6	70	08	9	70	09	9	65	14	9	60	14	9	60
06	6	75	03	9	75	04	9	70	09	9	65	09	9	65
07	9	75	06	6	75	08	9	70	04	9	70	15	9	65
01	6	80	07	9	75	10	9	70	08	9	70	04	9	70
02	9	80	01	6	80	03	9	75	10	9	70	08	9	70
			02	9	80	05	9	75	03	9	75	10	9	70
						07	9	75	05	9	75	03	9	75
						02	9	80				05	9	75

S_6			S_7			S_8			S_9			S_{10}		
ID	C_{ID}	SS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}
16	**6**	65	**13**	9	65	**14**	9	60	**19**	9		**14**	9	60
11	**6**	70	**16**	**6**	65	**18**	9	60	**14**	9	60	**20**	9	60
12	9	70	**08**	9	70	**09**	9	65	**20**	9	60	**09**	9	65
06	**6**	75	**11**	**6**	70	**13**	9	65	**09**	9	65	**15**	9	65
07	9	75	**12**	9	70	**04**	9	70	**13**	9	65	**04**	9	70
01	**6**	80	**03**	9	75	**08**	9	70	**15**	9	65	**08**	9	70
02	9	80	**06**	**6**	75	**10**	9	70	**04**	9	70	**10**	9	70
			07	9	75	**12**	9	70	**08**	9	70	**03**	9	75
			01	**6**	80	**03**	9	75	**10**	9	70	**05**	9	75
			02	9	80	**05**	9	75	**03**	9	75			
						07	9	75	**05**	9	75			

S_{11}			S_{12}			S_{13}			S_{14}			S_{15}		
ID	C_{ID}	SS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}
13	9	65	**18**	9	60	**14**	9	60	**14**	9	60	**14**	9	60
16	**6**	65	**13**	9	65	**18**	9	60	**18**	9	60	**20**	9	60
17	9	65	**16**	**6**	65	**24**	9	60	**20**	9	60	**09**	9	65
11	**6**	70	**17**	9	65	**09**	9	65	**24**	9	60	**15**	9	65
12	9	70	**08**	9	70	**13**	9	65	**09**	9	65	**25**	9	65
21	**6**	70	**11**	**6**	70	**16**	**6**	65	**13**	9	65	**10**	9	70
06	**6**	75	**12**	9	70	**17**	9	65	**15**	9	65	**05**	9	75
07	9	75	**21**	**6**	70	**23**	9	65	**25**	9	65			
01	**6**	80	**06**	**6**	75	**08**	9	70	**04**	9	70			
			07	9	75	**11**	**6**	70	**08**	9	70			
						12	9	70	**10**	9	70			
						21	**6**	70	**05**	9	75			
						22	9	70						
						07	9	75						

S_{16}			S_{17}			S_{18}			S_{20}			S_{21}		
ID	C_{ID}	SS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}
18	9	60	**18**	9	60	**14**	9	60	**14**	9	60	**18**	9	60
13	9	65	**13**	9	65	**18**	9	60	**18**	9	60	**13**	9	65
16	**6**	65	**16**	**6**	65	**20**	9	60	**20**	9	60	**16**	**6**	65
17	9	65	**17**	9	65	**24**	9	60	**24**	9	60	**17**	9	65
23	9	65	**23**	9	65	**13**	9	65	**09**	9	65	**23**	9	65
11	**6**	70	**11**	**6**	70	**16**	**6**	65	**15**	9	65	**11**	**6**	70
12	9	70	**12**	9	70	**17**	9	65	**25**	9	65	**12**	9	70
21	**6**	70	**21**	**6**	70	**23**	9	65	**10**	9	70	**21**	**6**	70
22	9	70	**22**	9	70	**25**	9	65				**22**	9	70
06	**6**	75				**08**	9	70						
						12	9	70						
						21	**6**	70						
						22	9	70						

s_{22}			s_{23}			s_{24}			s_{25}		
ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}	ID	C_{ID}	RSS_{CH}
18	9	60	**18**	9	60	**14**	9	60	**14**	9	60
16	**6**	65	**24**	9	60	**18**	9	60	**18**	9	60
17	9	65	**13**	9	65	**20**	9	60	**20**	9	60
23	9	65	**16**	**6**	65	**24**	9	60	**24**	9	60
12	9	70	**17**	9	65	**13**	9	65	**15**	9	65
21	**6**	70	**23**	9	65	**15**	9	65	**23**	9	65
22	9	70	**25**	9	65	**23**	9	65	**25**	9	65
			21	**6**	70	**25**	9	65	**22**	9	70
			22	9	70						

Figure 6.14. Sorted SRN tables for all nodes.

Let us examine the SRN table of one node in detail. The SRN table of s_1 is shown in Figure 6.15. SRN table shows that s_1 cannot decide its power state first. It has to wait for node s_2 to decide its power state. On the other hand, the SNR table of s_2 shows that it can decide its power state first without any deadlock and race conditions (cf. Figure 6.16). Once all deployed sensor nodes determine their decision order, then they can decide their power states in parallel (making them either active or passive) in each cluster.

After finding decision order for active/passive decision, the process for determining the state of wireless sensor nodes starts. The sensor nodes that switched to active power mode are active sensor nodes (they will become regular nodes and cluster heads), and the rest are passive sensor nodes (they will become spares).

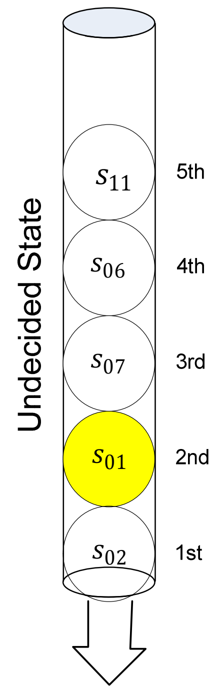


Figure 6.15. The order in which node s_1 makes the spare/primary decision.

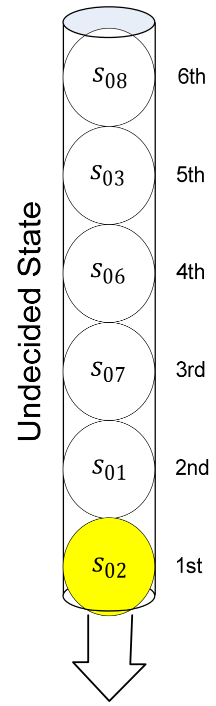


Figure 6.16. The order in which node s_2 makes the spare/primary decision.

6.2.2.4 Example 2: Nodes Making the Spare/Primary Decision (Output of Algorithm 2)

To understand how sensor nodes decide their power state, especially those who at the boundary of the cluster, let us consider the sorted SRN table of all the deployed sensor nodes. According to the algorithm each sensor node sorts its SRN table. The sorting process is primarily based on the received signal strength RSS_{CH}. The overall picture after sorting SRN tables according to our designed algorithm is shown in Figure 6.14.

Determining the power state of sensor nodes is divided into rounds. Each round represents a single clock tick, that is, on each clock tick sensor nodes decide their power state in parallel.

Round 1: In the first round all sensor nodes check their entries in their respective sorted SRN tables. The SRN table for sensor node s_2 shows that it is the first from bottom, that is, s_2 is getting weak signal (that is, it will consume more energy in order to communicate reciprocally with the cluster head). The SRN table for sensor node s_5 shows that it is at 1st place from the bottom, that is, s_2 has a weaker signal strength than s_3.

Similarly the SRN table of sensor node s_{22} shows that it is at the first place. Therefore, the nodes s_2, s_5 and s_{22} can decide in parallel their power state in the first round.

Let us consider node s_2. Node s_2 is trying to find out whether $SRN^{-}(s_2)$ are covering the targets that are covered by s_2 or not.

The targets covered by $s_1,\ s_2, s_{7,} s_6, s_3$ and s_8 are:

$TS(s_1) = \{A, D, F\}$

$TS(s_2) = \{A, B, D, F\}$

$TS(s_7) = \{A, B, D, E, F, G\}$

$TS(s_6) = \{A, D, F, I, J\}$

$TS(s_3) = \{B, C, D, F\}$

$TS(s_8) = \{A, B, C, D, E, F, G\}$

Note that $SRN^{-}(s_2) = \left\{s_1, s_{7,} s_6, s_3, s_8\right\}$.

Then we get:

$\cup\{TS(s_1), TS(s_7), TS(s_6), TS(s_3), TS(s_8)\} = \{A, B, C, D, E, F, G, I, J\}$

The union gives the set of all targets covered by $SRN^{-}(s_2)$, so s_2 knows what targets are covered by $SRN^{-}(s_2)$. Now, s_2 takes the intersection of the union with the set of targets that it covers:

$$\bigcup\{TS(s_1), TS(s_7), TS(s_6), TS(s_3), TS(s_8)\} \cap TS(s_2) = \{A, B, D, F\} = TS(s_2)$$

Thus, s_2 should become a spare as shown in Figure 6.17. Before becoming a spare, s_2 transmits its decision to all members of the SR-neighbor set $SRN^{-}(s_2)$. After receiving the decision message from s_2, all its SR-neighbors from $SRN^{-}(s_2)$ update their SRN tables and mark s_2 as a spare. Next they delete the entry for s_2 from their SRN tables (because s_2 is not covering any target covered by them).

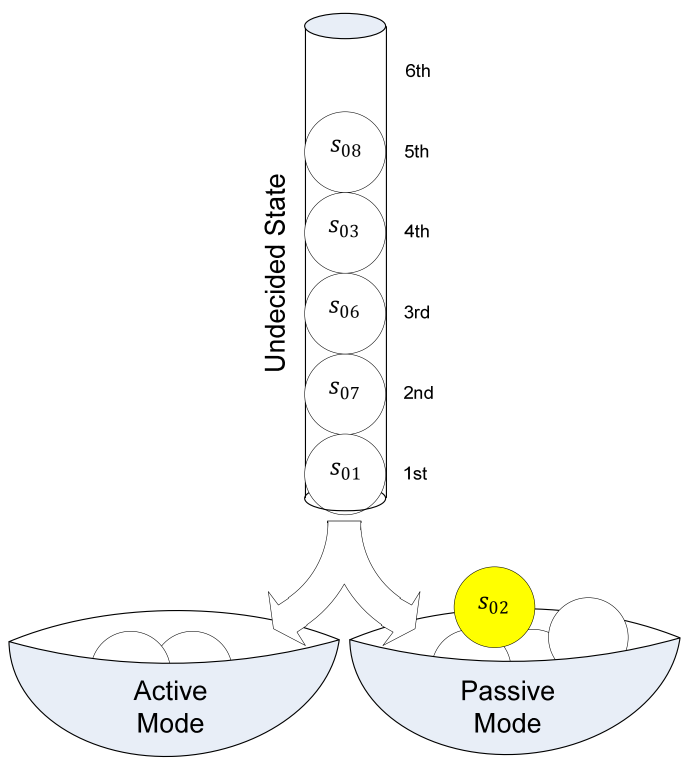


Figure 6.17. The node s_2 becomes a spare (switches into passive mode) as decided by DESST during the spare selection phase.

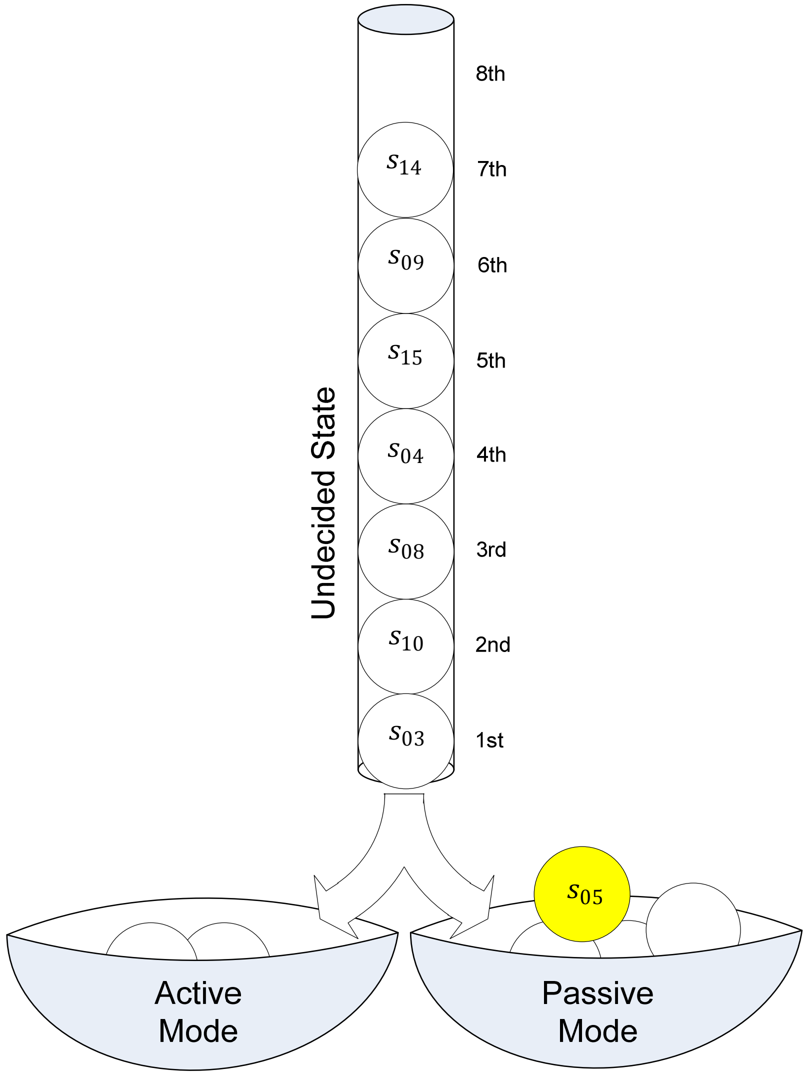


Figure 6.18. The node s_5 becomes a spare as decided by DESST.

Next we consider node s_5 to find out whether $SRN^{-}(s_5)$ are covering the targets that are covered by s_2 or not. The $SRN(s_5)$ are s_{14}, $s_9, s_{15,} s_4, s_8, s_{10}, s_3$, and s_5

The targets covered by s_{14}, $s_9, s_{15,} s_4, s_8, s_{10}, s_3$, and s_5 are:

$TS(s_{14}) = \{C, E, G, H, K\}$

$TS(s_9) = \{B, C, D, E, G, H, K\}$

$TS(s_{15}) = \{C, E, G, H, K\}$

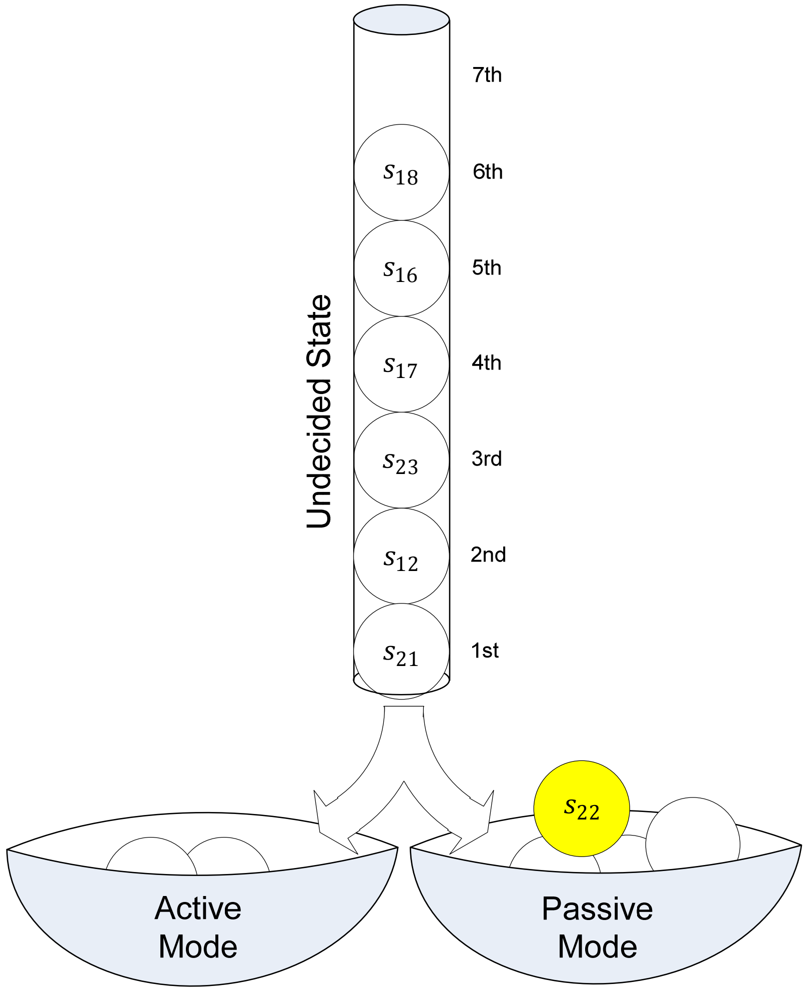


Figure 6.19. The node s_{22} becomes a spare.

$TS(s_4) = \{B, C, D, E\}$

$TS(s_8) = \{A, B, C, D, E, F, G\}$

$TS(s_{10}) = \{B, C, E, G, H, K\}$

$TS(s_3) = \{B, C, D, E\}$

$TS(s_5) = \{B, C, E\}$

Note that $SRN^{-}(s_5) = \{s_{14}, s_9, s_{15}, s_4, s_8, s_{10}, s_3\}$.

Then, we get:

$\bigcup\{TS(s_{14}), TS(s_9), TS(s_{15}), TS(s_4), TS(s_8), TS(s_{10}), TS(s_3), TS(s_5)\} =$

$= \{C, E, G, H, K, B, D, A, F\}$

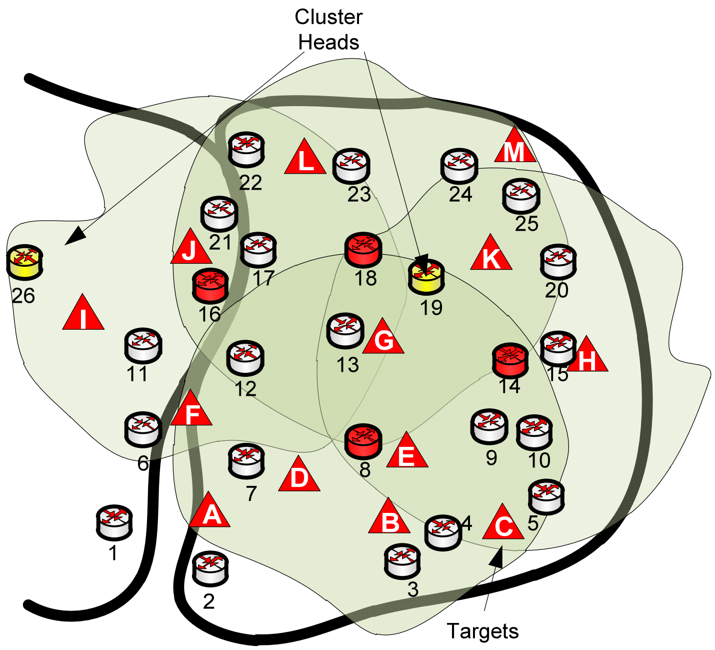


Figure 6.20. Illustration of selecting primary/spare status.

The union gives the set of all targets covered by $SRN^{-}(s_5)$, so s_5 knows what targets are covered by $SRN^{-}(s_2)$. Now, s_5 takes the intersection of the union with the set of targets that it covers:

$\bigcup\{TS(s_{14}), TS(s_9), TS(s_{15}), TS(s_4), TS(s_8), TS(s_{10}), TS(s_3), TS(s_5)\} \cap TS(s_5) =$

$= TS(s_5)$

Thus, s_5 should switch into the passive mode as shown in Figure 6.17. Before switching into the passive mode, s_2 transmits its decision to all members of the neighbor set $SRN^{-}(s_2)$. After receiving the decision message from s_2, all his SR-neighbors from

$SRN^{-}(s_2)$ update their SRN tables and mark s_2 as passive. Next, they delete the entry for s_2 from their SRN tables (because s_2 is is not covering any target covered by them).

Similarly s_{22} should switch into the passive mode as shown in Figure 6.19. Thus in first round nodes s_2, s_5 and s_{22} decided their power mode in parallel.

After 13 rounds, all 26 nodes have decided their primary/spare status. Only four nodes (s_8, s_{14}, s_{16} and s_{18}) became primaries, as shown in Figure 6.20.

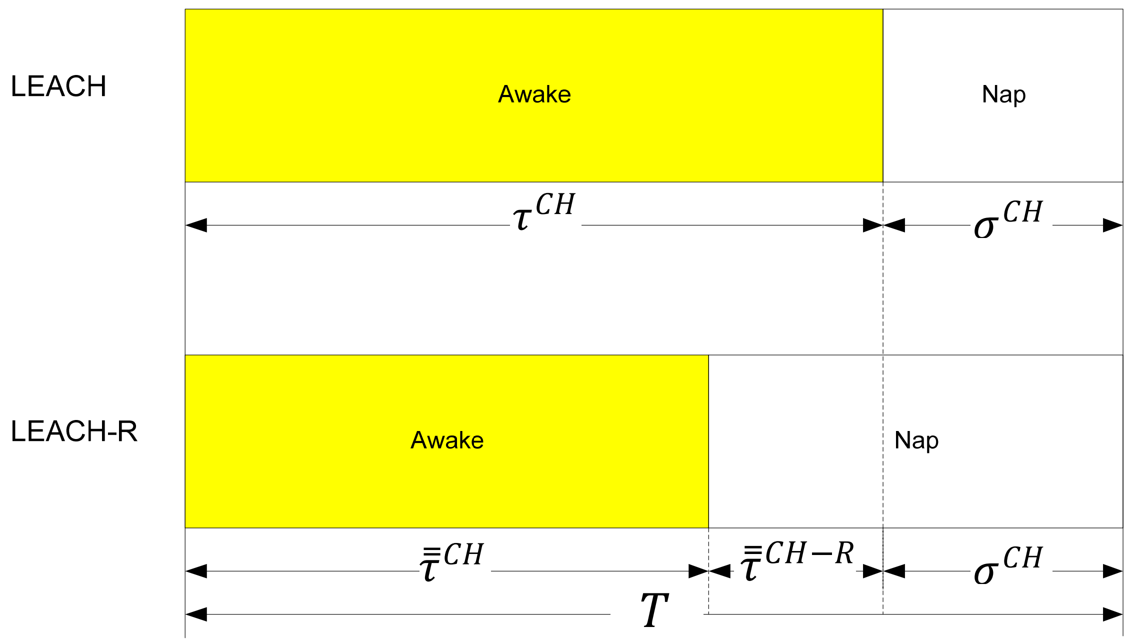


Figure 6.21. The frame structure and timing of frame components for cluster heads in LEACH and LEACH-SM.

7. MANAGEMENT AND SCHEDULING OF SPARE SENSOR NODES

Use of redundancy techniques to extend WSN lifetime is a common practice. Extending means that WSN performs satisfactorily for a longer time. In the context of using redundancy, such extension can only be achieved by efficiently scheduling and managing redundant sensor nodes.

7.1 Management of Redundant Sensor Nodes

As mentioned before, there are many factors involved in extending WSN lifetime, but minimizing the number of sensor nodes in active mode while maintaining the required target coverage, and optimal scheduling of the redundant sensor nodes are the major factors in extending WSN lifetime. To extending WSN lifetime networks lifetime we need to satisfy the following two conditions in each round.

Selection of spares: Maximize the number of spares while assuring the minimum required target coverage. At the moment of deployment, the spares are in the Asleep state. This results in reducing the transmission of redundant data from regular nodes to their cluster heads. It also reduces the workload on cluster heads (since cluster heads are responsible for data aggregation).

Scheduling of spares: Optimize replacement of exhausted primaries by spares. The duration of the Asleep interval for spares should be properly calculated so that they can conserve their battery power (and thus extend the WSN lifetime). Once the Asleep interval ends at time t, the spares (which spend most of their time napping) get periodically awakened to check if their cluster heads needs them for replacing an exhausted primary node. This mode of operations results in a slow, gradual curtailment of their power. For this approach to work, we need to find the time t, after which the probability of energy exhaustion for a sensor node in the cluster is appropriately high.

7.2 Selecting Spares

We already presented the DESST scheme which properly switches the sensor nodes from undecided state to passive or active mode.

7.3 Scheduling Spares

Spares have significant influence on the WSN lifetime. We can extend WSN lifetime by efficient scheduling of spares. The Asleep interval for spares should be properly determined so that they can conserve their battery power but (with high probability) not "oversleep" the moment when they are needed to replace an exhausted primary.

We say that *WSN is healthy* when no primary requires replacement. Checking WSN health by a spare means that the spare checks with its cluster head if any primary requires a replacement.

Sensor nodes get activated periodically to check WSN health. As illustrated in Figure 7.1, the Awake interval for spares is small compared to the Awake interval for cluster heads and regular nodes. Yet, spare operations involve a gradual curtailment of its power.

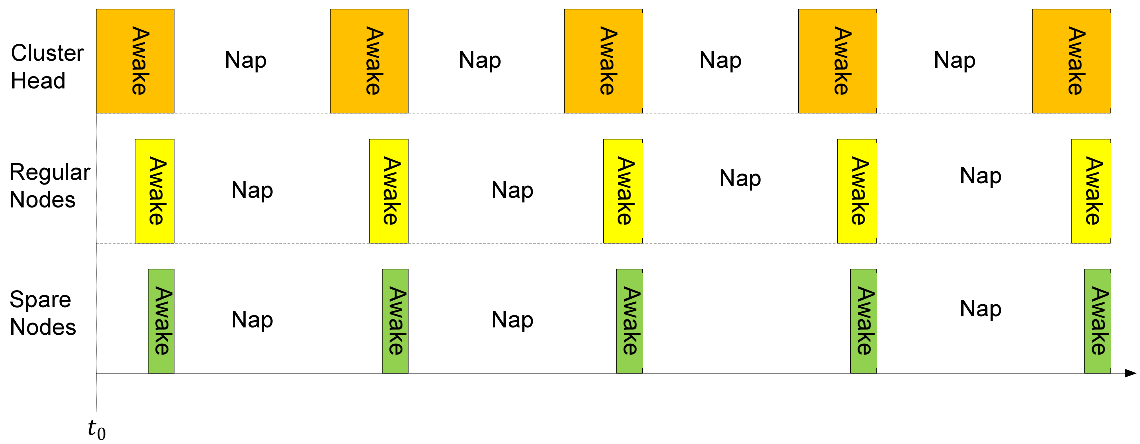


Figure 7.1. Awake/Nap cycles for primaries and spares in LEACH-SM.

The chance of exhausting energy by any sensor node in the beginning (close to the moment of WSN deployment) is very low. Therefore, we introduced the Asleep interval for spares, as shown in Figure 7.2. After the spare selection phase, the Asleep interval starts for spares. During this interval, the base station broadcasts a short message, containing information on the endpoint t for the sleep interval $[0, t]$. Alternatively, the duration t of the Asleep interval could be communicated to each node before WSN deployment. In such a case, the base station would not be required to broadcast the value of t to the sleeping spares. In both cases information about the value of t is passed to all sensor nodes only once.

Spares in the Asleep state till time t can save 100% energy during the interval $[0, t]$ by sleeping. At time t spares enter the Awake/Nap cycles, as shown in Figure 7.2. The figure shows that their Awake periods are synchronized with the end of the Awake periods for their cluster heads. In case if any regular node exhausts its energy, the spare assumes its functions.

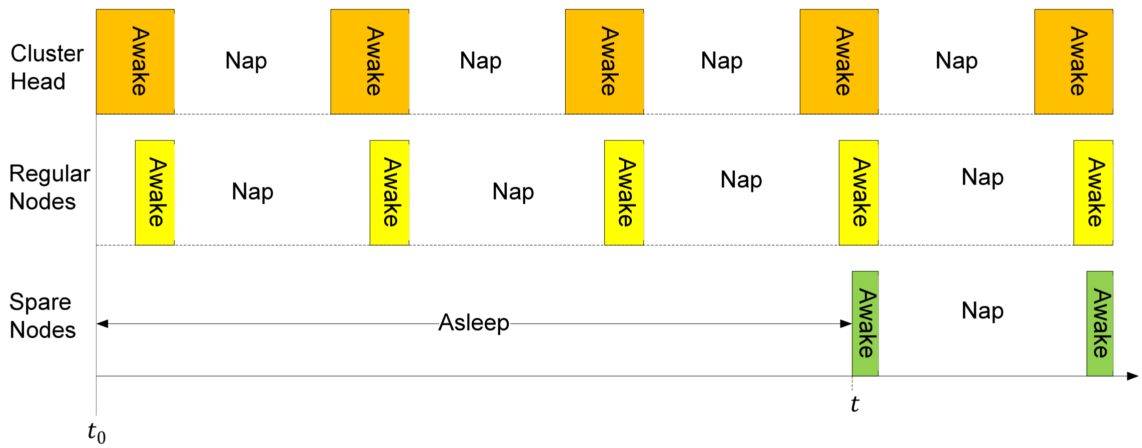


Figure 7.2. Duty cycle of active and spare nodes in LEACH-SM, in which the spares follow the Awake/Nap cycle from time *t*.

We find value of t as follows. On one hand, it should be as large as possible to maximize saving battery power. On the other hand, it cannot be too large, because we want to start checking WSN health at some point after deployment when the chances of energy exhaustion by any primary are appropriately high.

It is based on awaking spares at time *t*, when the probability that any primary node exhausted its energy reaches a predefined value. At this time, after their asleep period is over, all spares enter their awake/nap cycles.

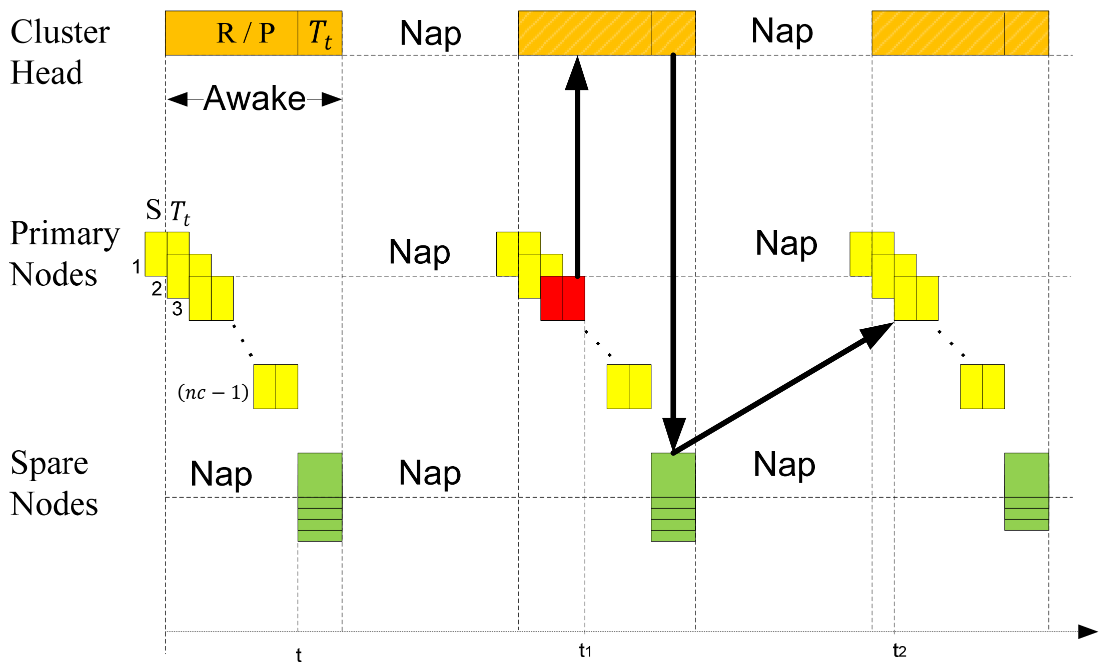


Figure 7.3. The replacement process for a primary that exhausted its energy. (R/P indicates receiving and processing data interval. S and T_t are the sensing interval and data transmission interval respectively.)

Figure 7.3 shows that at time t_1 the regular sensor node s_i exhausts its energy. The cluster head easily detects the unavailability of s_i (because it receives no more sensing data from it) and broadcasts message to all spares that one of them is needed for replacement. Then the appropriate spare turns itself on. Thus at time $t_2 = (T - (S + T_t))$ the replacement process completes (T is frame length).

7.4 The State Diagram for Nodes During Execution of LEACH-SM

During the execution of LEACH-SM a node could be in one of 7 states as shown in Figure 7.4. After the deployment all nodes are in an undecided state. After running the Decentralized Energy-efficient Spare Selection Technique (DESST), each node decides if it should become a primary or a spare. In the former case, the node enters the *active* state (it will enter the cycles of Awake and Nap intervals when the spare selection phase ends).

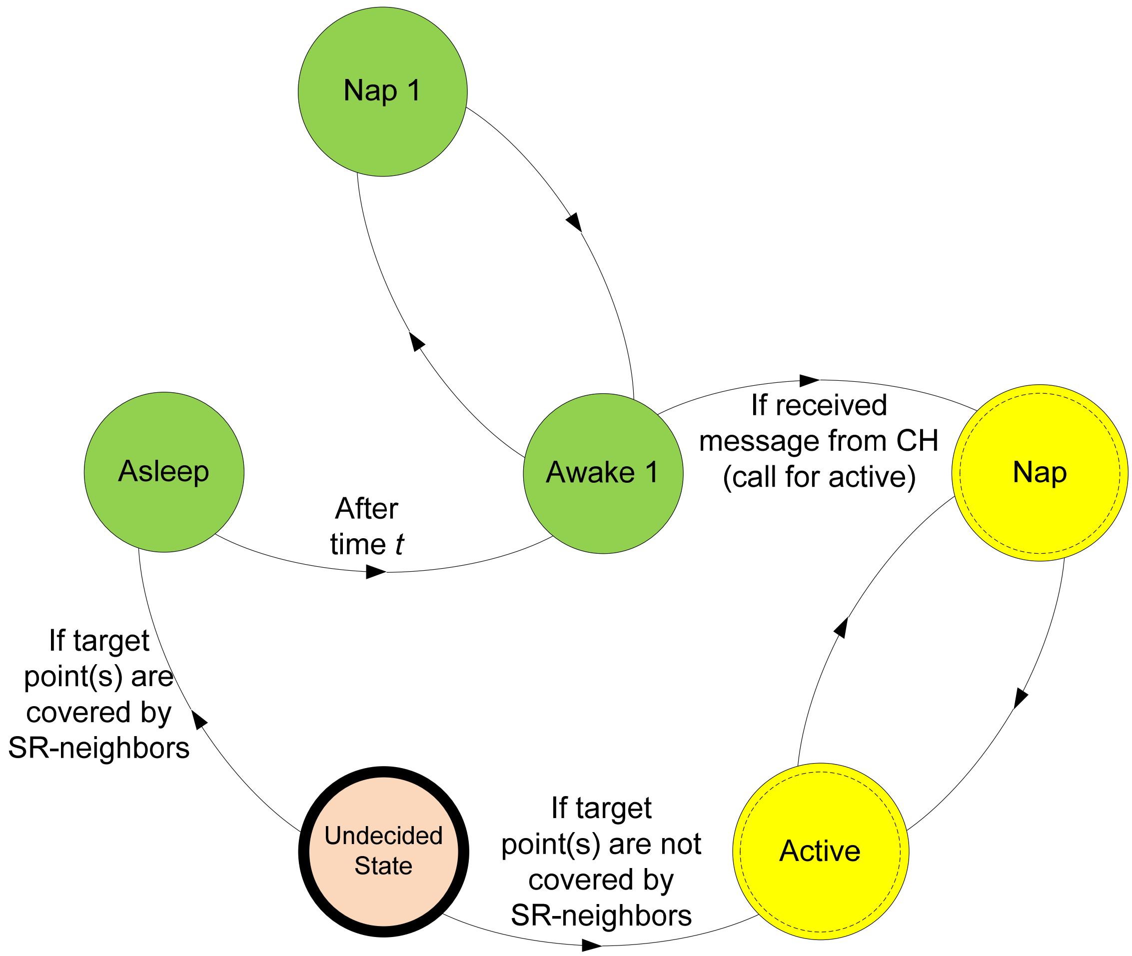


Figure 7.4. The state diagram for nodes states during execution of LEACH-SM.

In the latter case, the node enters the *passive* power mode (it will go Asleep at the moment when the spare selection phase ends).

After time t , a spare enters the Awake 1 state. If it does not receive message from its cluster head, then it moves into the Nap 1 state and synchronizes itself with the cluster head; otherwise, it moves into the Awake 2 state.

8. ANALYTICAL COMPARISON OF WSN LIFETIME FOR LEACH AND LEACH-SM

We modified the LEACH protocol into the LEACH-SM protocol in order to increase WSN lifetime.

8.1 Timeline of LEACH-SM

To achieve WSN lifetime extension, LEACH-SM adds the *spare selection* phase to LEACH, as shown in Figure 8.1 (there is no *spare selection* phase in LEACH, as shown in Figure 5.1).

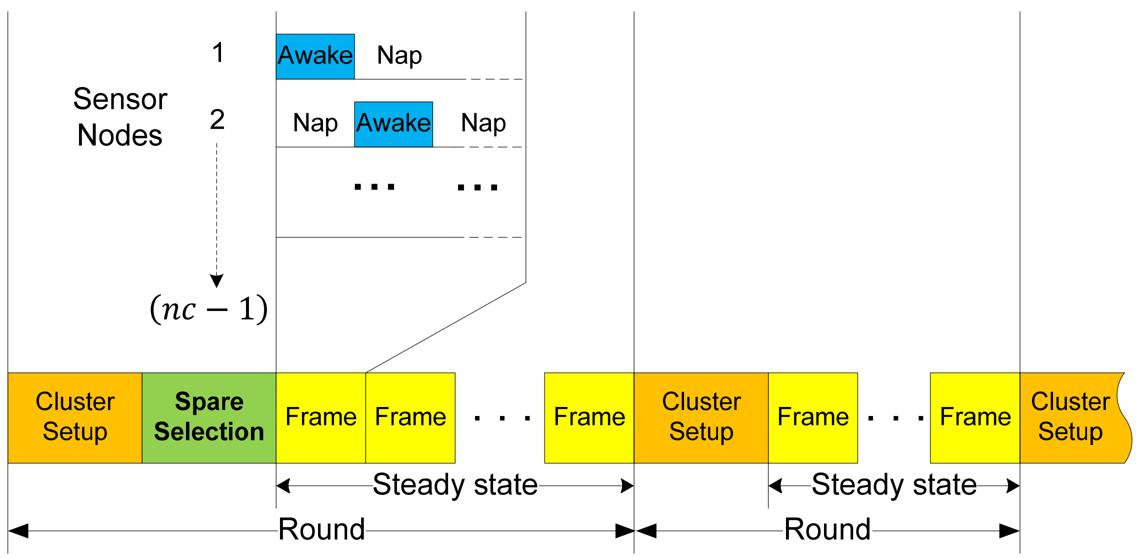


Figure 8.1. Rounds, phases, and frames for LEACH-SM, including the added spare selection phase.

During this added *spare selection* phase, Decentralized Energy-efficient Spare Selection Technique (DESST) is run. DESST, described in Chapter 6, is a management technique that allows each node to decide whether it should become a primary node or a spare.

8.2 Calculating Duration of Awake Interval for LEACH-SM

In this section, we calculate durations of the Awake intervals for cluster heads and regular nodes, and duration of the Nap interval for cluster heads.

8.2.1 Duration of Awake Interval for Regular Sensor Nodes

The length $\bar{\bar{\tau}}^{Reg}$ of the Awake interval for a regular node in LEACH-SM is the same as in LEACH:

$$\bar{\bar{\tau}}^{Reg}(r, l, l^*) = \tau_{sen+log}^{Reg}(l) + \tau_{snd}^{Reg}(l^*, r)\ [sec] \tag{8.1}$$

8.2.2 Duration of Awake Interval for Cluster Head

Consider nc nodes in a cluster. One of them becomes a cluster head, and the remaining $nc - 1$ will become regular nodes or spares. Let $\alpha\%, 0 \leq \alpha < 100,$ be the ratio of the cluster nodes that become spares. That is, $\lfloor (nc - 1) \times \alpha \rfloor$ nodes become spares, and $\lfloor (nc - 1)(1 - \alpha) \rfloor$ nodes become regular nodes.

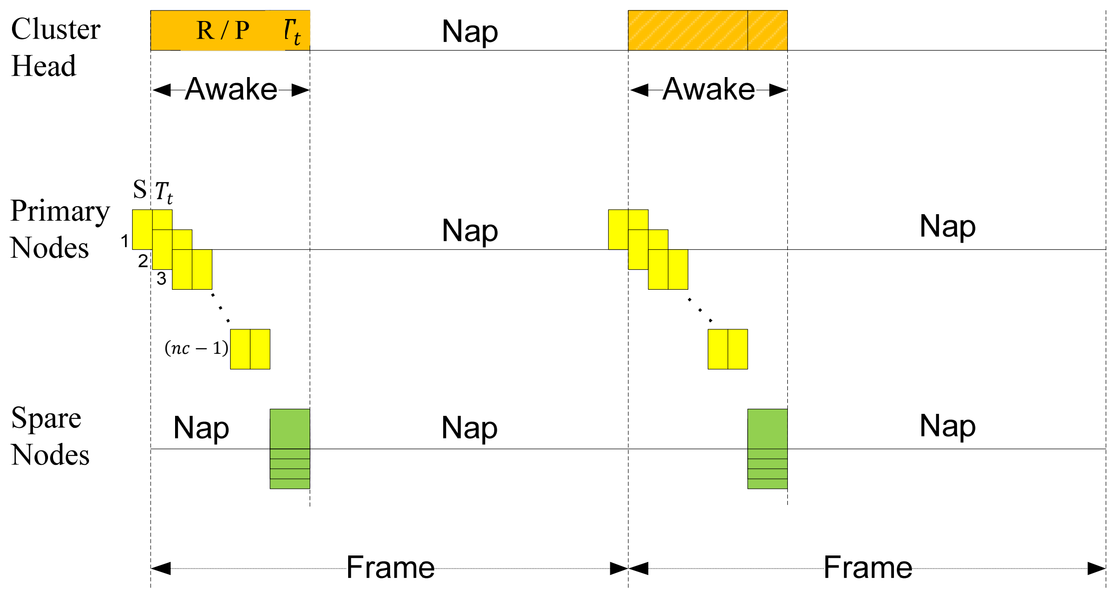


Figure 8.2. Timing of awake and nap intervals for a cluster head and its $\lfloor (nc-1)(1-\alpha) \rfloor$ regular nodes. (Awake periods shown in gray, and Nap periods shown in white.)

As a result of having the above number of spares, the workload of the cluster head is reduced by α. Consequently the receiving window size for the cluster head is:

$$\bar{\bar{\tau}}_{rcv+log}^{CH}(\alpha, l^*, nc, r) = \lfloor (nc-1)(1-\alpha) \rfloor \times \tau_{snd}^{Reg}(l^*, r)\ [sec] \tag{8.2}$$

Time taken by a cluster head for data aggregation depends upon the number and size of messages received from regular nodes. Let t_{agg} be the average time taken by the cluster head to aggregate one bit of data ([sec/bit]). The cluster head receives $\bar{\bar{b}}_{rec}^{CH} = (nc-1)(1-\alpha) \times l^*$ [bits]. Hence, time used by a cluster head for data aggregation is:

$$\bar{\bar{\tau}}_{agg}^{CH}(\alpha, l^*, nc, t_{agg}) = t_{agg} \times b_{rec}^{CH}\ [sec]$$

$$= t_{agg} \times (nc-1)(1-\alpha) \times l^*\ [sec] \tag{8.3}$$

Regular nodes with overlapping target coverage generate redundant data. After receiving all data from regular nodes, the cluster head aggregates received data, reducing data size by a factor of β [%]; $0 \leq \beta < 100$. Since the total size of sensed data received by a cluster head is $\bar{\bar{b}}_{rec}^{CH} = (nc-1)(1-\alpha) \times l^*$ [bits], then the size $\bar{\bar{b}}_{agg}^{CH}$ of data aggregated by cluster head is:

$$\bar{\bar{b}}_{agg}^{CH}(\alpha, \beta, l^*, nc) = \beta \times (nc-1)(1-\alpha) \times l^* \text{ [bits]} \tag{8.4}$$

The average time $\bar{\bar{\tau}}_{snd}^{CH}$ taken by the cluster head to forward the aggregated data to its base station at the transmission rate *r* [bits/sec] is:

$$\bar{\bar{\tau}}_{snd}^{CH}(\alpha, \beta, l^*, nc, r) = \bar{\bar{b}}_{agg}^{CH}(\alpha, \beta, l^*, nc)/\, r\, [sec]$$

$$= \beta \times (nc-1)(1-\alpha) \times l^* /\, r\, [sec] \tag{8.5}$$

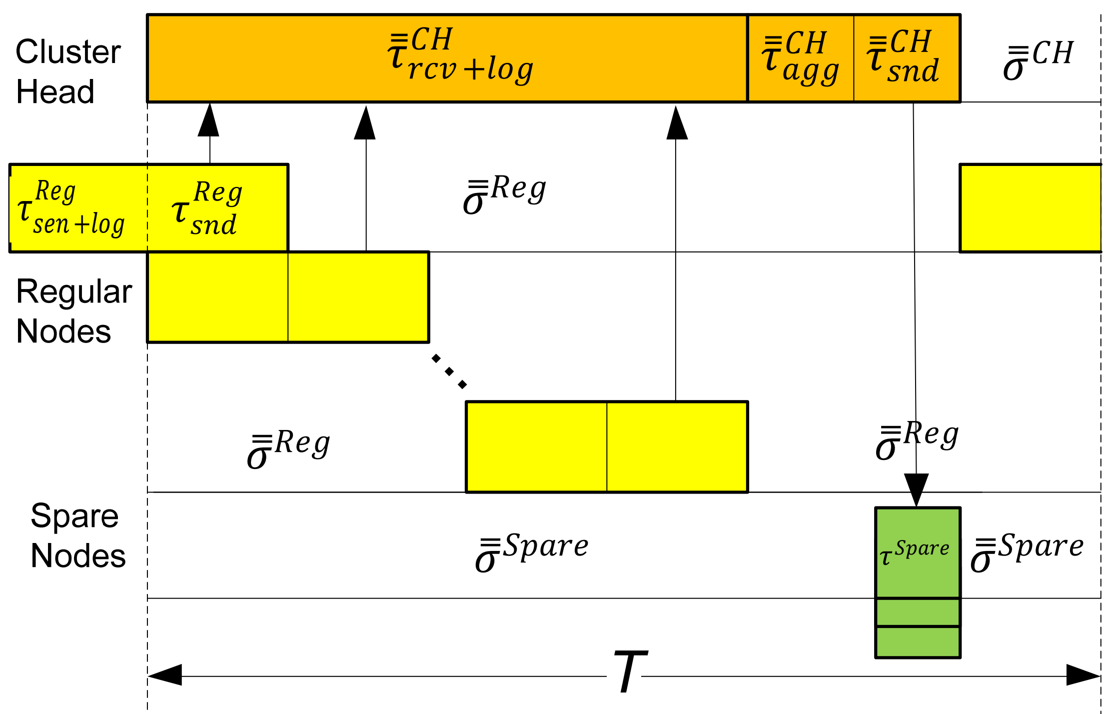


Figure 8.3. Timeline of activities for each type of sensor node in LEACH-SM.

The Awake intervals for spare nodes (shown in gray at the bottom of Figure 8.3) overlap because all spares awake simultaneously from their nap just to listen to a broadcast from their cluster head (which might call upon a given spare or spares to replace exhausted regular nodes). The arrows from regular nodes to cluster head denote transmissions of sensed data; the arrows from cluster head to spares represent the broadcast from their cluster head.

As Figure 8.3 indicates, the total average time during which the cluster head remains Awake is:

$$\bar{\bar{\tau}}^{CH}(\alpha,\beta,l^*,nc,r,t_{agg})$$
$$= \tau_{rcv+log}^{CH}(\alpha,l^*,nc,r) + \tau_{agg}^{CH}(\alpha,l^*,nc,t_{agg}) + \tau_{snd}^{CH}(\alpha,\beta,l^*,nc,r)\ [sec] \qquad (8.6)$$

8.2.3 Duration of Nap Interval for Cluster Head

The Nap interval for the cluster head is:

$$\bar{\bar{\sigma}}^{CH}(\alpha,\beta,l^*,nc,r,t_{agg},T) = T - \bar{\bar{\tau}}^{CH}(\alpha,\beta,l^*,nc,r,t_{agg})\ [sec] \qquad (8.7)$$

If a cluster head remains Awake continuously, then $\bar{\bar{\sigma}}^{CH} = 0$, otherwise $\bar{\bar{\sigma}}^{CH} > 0$.

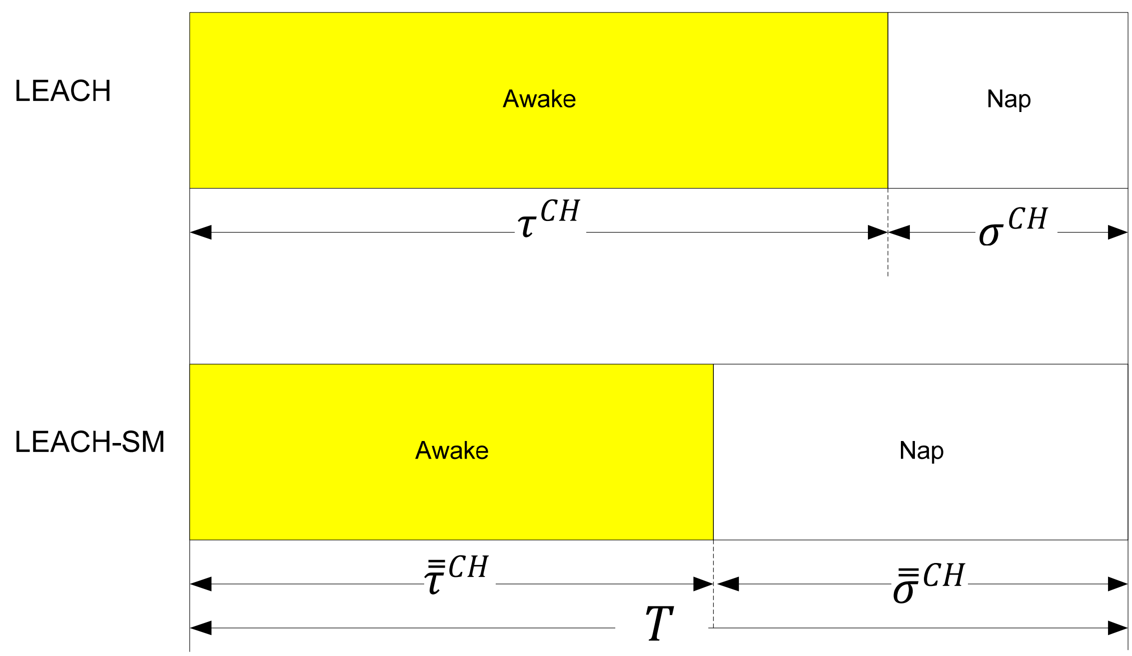


Figure 8.4. Comparison of cluster head activities in LEACH and LEACH-SM.

8.3 Calculating the Duty Cycle for LEACH-SM

Consider the same frame length T for LEACH-SM as was used for LEACH (cf. Figure 8.4). Having the same frame length enables us to compare the duty cycles of cluster heads in both protocols.

8.3.1 Case 1: Duration of Nap Interval for Cluster Head is Zero

Similarly as we did for LEACH, we will calculate the duty cycle of cluster head first. Here $\bar{\bar{\sigma}}^{CH} \geq \sigma^{CH}$.

8.3.1.1 Calculating the Duty Cycle for Cluster Head

The duration of Awake interval for cluster head is:

$$\bar{\bar{\tau}}^{CH}(\alpha,\beta,l^*,nc,r,t_{agg}) = \bar{\bar{\tau}}^{CH}_{rcv+log}(\alpha,l^*,nc,r) + \bar{\bar{\tau}}^{CH}_{agg}(\alpha,l^*,nc,t_{agg}) + \bar{\bar{\tau}}^{CH}_{snd}(\alpha,\beta,l^*,nc,r)\ [sec]$$

or

$$\bar{\bar{\tau}}^{CH}(\alpha,\beta,l^*,nc,r,t_{agg}) = \tau^{CH}(1-\alpha) \times 100[\%] \quad (8.8)$$

This shows that:

$$\bar{\bar{\tau}}^{CH}(\alpha,\beta,l^*,nc,r,t_{agg}) \leq \tau^{CH} \quad (8.9)$$

In this case, the duty cycle of a cluster head is:

$$\bar{\bar{d}}^{CH}(\alpha,\beta,l^*,nc,r,t_{agg},T) = \bar{\bar{\tau}}^{CH}\,/\,T = \tau^{CH} \times (1-\alpha)\,/\,T =$$

$$= d^{CH} \times (1-\alpha) \times 100[\%] \leq d^{CH} \quad (8.10)$$

If $\alpha > 0$, the cluster head will not remain in the Awake mode continuously. As compared to LEACH, the duty cycle decreased by α %.

8.3.1.2 Calculating the Duty Cycle for Regular Nodes

The duty cycle for a regular node is:

$$\bar{\bar{d}}^{Reg}(r,l,l^*,T) = \bar{\bar{\tau}}^{\mathrm{Reg}}(r,l,l^*)/T =$$

$$\frac{\tau^{\mathrm{Reg}}(r,l,l^*) \times (1-\alpha)}{T} = d^{Reg} \times (1-\alpha) \times 100[\%] \leq d^{Reg}(r,l,l^*,T) \tag{8.11}$$

8.3.1.3 Calculating the Duty Cycle for Spare Nodes

If the Awake interval for a spare is $\bar{\bar{\tau}}^{Spare}$ and l^c is the length of the control message from the cluster head, then its duty cycle $\bar{\bar{d}}^{spare}$ is:

$$\bar{\bar{d}}^{Spare}(l^c,T) = \bar{\bar{\tau}}^{Spare}/\mathrm{T} \tag{8.12}$$

8.3.2 Case 2: Duration of Nap Interval for Cluster Head is Not Zero

We calculate the duty cycle for all node types in turn.

8.3.2.1 Calculating the Duty Cycle for Cluster Head

If $\sigma^{CH} > 0$, then the duty cycle for the cluster head is:

$$\bar{\bar{d}}^{CH}\left(\alpha,\beta,l^*,nc,r,t_{agg},T\right) = \frac{\bar{\bar{\tau}}^{CH}}{T} =$$

$$\tau^{CH} \times (1-\alpha)/T = d^{CH} \times (1-\alpha) \times 100[\%] \tag{8.13}$$

8.3.2.2 Calculating the Duty Cycle for Regular Nodes

The duty cycle for a regular node is:

$$\bar{\bar{d}}^{Reg}(\mathrm{r},\mathrm{l},\mathrm{l}^*,\mathrm{T}) = \frac{\bar{\bar{\tau}}^{Reg}}{T} = \frac{\tau^{Reg} \times (1-\alpha)}{T}$$

$$= d^{Reg} \times (1 - \alpha) \times 100[\%] \leq d^{Reg}(r, l, l^*, T) \quad (8.14)$$

8.3.2.3 Calculating the Duty Cycle for Spare Nodes

Similarly as before, the duty cycle for a spare is:

$$\bar{\bar{d}}^{Spare}(l^c, T) = \bar{\bar{\tau}}^{Spare}/\mathrm{T} \quad (8.15)$$

8.4 Energy Consumption Model for LEACH-SM

In this section, we derive the energy consumption model for LEACH-SM.

8.4.1 Average Current Drawn by Regular Nodes

The energy consumption model for regular nodes used for LEACH applies to LEACH-SM as well. Hence, the average current consumed by a regular node during its Awake interval is (parameter lists omitted):

$$I^{Reg} = \frac{\left(\tau^{Reg}_{sen+log} \times I^{Reg}_{sen+log}\right) + \left(\tau^{Reg}_{snd} \times I^{Reg}_{snd}\right)}{\tau^{Reg}_{sen+log} + \tau^{Reg}_{snd}} [A] \quad (8.16)$$

where $I^{Reg}_{sen+log}$ and I^{Reg}_{snd} are the average currents used by the regular node during sensing and logging (storing) and transmitting (sending) to cluster head, respectively.

8.4.2 Average Current Drawn by Cluster Heads

The average current drawn by a cluster head during its Awake interval is:

$$\bar{\bar{I}}^{CH} = \frac{\left(\bar{\bar{\tau}}^{CH}_{rcv+log} \times I^{CH}_{rcv+log}\right) + \left(\bar{\bar{\tau}}^{CH}_{agg} \times I^{CH}_{agg}\right) + \left(\bar{\bar{\tau}}^{CH}_{snd} \times I^{CH}_{snd}\right)}{\bar{\bar{\tau}}^{CH}_{rcv+log} + \bar{\bar{\tau}}^{CH}_{agg} + \bar{\bar{\tau}}^{CH}_{snd}} [A] \quad (8.17)$$

where $I_{rcv+log}^{CH}$, I_{agg}^{CH}, and I_{snd}^{CH} are the average currents drawn by the cluster head during receiving and logging messages, data aggregation, and sending data to the base station.

8.4.3 Average Current Drawn by Spares

The average current drawn by a spare during its Awake interval is:

$$I^{Spare} = I_{rcv+log}^{CH} \tag{8.18}$$

8.5 Special-case Calculation of WSN Lifetime for LEACH-SM

As we did for LEACH, also here we limit ourselves to a special-case calculation of WSN lifetime.

To estimate WSN lifetime in LEACH-SM, we first calculate the lifetime of individual sensor nodes (cluster heads or regular sensor nodes) performing different duties.

Theorem 3: Let B_{cap} $[Ah]$ be the initial battery charge; I^{Setup}, I^{ss} —the average currents drawn by a node during the cluster setup phase and spare selection, respectively; I^{Reg} —the average current drawn by a regular node (more precisely, a node playing the role of a regular node) during its Awake interval; $\bar{\bar{I}}^{CH}$ —the average current drawn by the cluster head (more precisely, by a node playing the role of a cluster head) during its Awake interval; R —the number of rounds; and $\bar{\bar{\tau}}^{Setup}$, τ^{ss}, $\bar{\bar{\tau}}^{Reg}$ and $\bar{\bar{\tau}}^{CH}$ —the durations of the setup phase, the spare selection phase, and the Awake intervals for a regular node and a cluster head, respectively. Then, the number of frames $\bar{\bar{F}}$ per round in LEACH-SM is:

$$\bar{\bar{F}} = \left\lfloor \frac{3600 \times B_{cap}[Ah] - \left(\bar{\bar{I}}^{Setup} \times \bar{\bar{\tau}}^{Setup} \times R\right) - \left(\bar{\bar{I}}^{ss} \times \bar{\bar{\tau}}^{ss}\right)}{\left(\bar{\bar{I}}^{CH} \times \bar{\bar{\tau}}^{CH}\right) + \bar{\bar{I}}^{Reg} \times \bar{\bar{\tau}}^{Reg} \times (R-1)} \right\rfloor \tag{8.19}$$

The proof of Theorem 3 is analogous to the proof of Theorem 1. It is omitted to avoid redundancy.

Theorem 4: Let $\bar{\bar{F}}$ be the number of frames per round, *R*—the number of rounds during the entire WSN lifetime, τ^{Setup}—the duration of the setup phase, and *T*—the duration of each frame. Then, WSN lifetime $\bar{\bar{L}}$ for LEACH-SM is:

$$\bar{\bar{L}} = (\bar{\bar{\tau}}^{CH} \times \bar{\bar{F}})/\bar{\bar{d}}^{CH} +$$

$$+ \frac{3600 \times B_{cap} - \left(\bar{\bar{I}}^{Setup} \times \bar{\bar{\tau}}^{Setup} \times R\right) - \left(\bar{\bar{I}}^{CH} \times \bar{\bar{\tau}}^{CH} \times \bar{\bar{F}}\right) - \left(\bar{\bar{I}}^{ss} \times \bar{\bar{\tau}}^{ss}\right)}{\bar{\bar{I}}^{Reg} \times \bar{\bar{d}}^{Reg}} \tag{8.20}$$

The proof of Theorem 4 is analogous to the proof of Theorem 2. It is omitted to avoid redundancy.

8.6 Spare Lifetime and Residual Spare Lifetime in LEACH-SM

If a node is a spare forever (never becomes a primary), then its lifetime can be calculated as follows:

$$L^{Spare} = Asleep\ interval\ duration + \frac{B_{cap}}{I_{rcv+log}^{CH} \times d^{spare}} \tag{8.21}$$

The residual lifetime for a spare at time t is:

$$L_{Spare}^{Resi}\Big|_t = L^{Spare} - t \quad 0 \leq t \leq L^{Spare} \tag{8.22}$$

8.7 Residual WSN Lifetime for LEACH-SM

The residual WSN lifetime at time t is:

$$\bar{\bar{L}}^{Resi}\Big|_t = \bar{\bar{L}} - t \quad 0 \leq t \leq \bar{\bar{L}} \tag{8.23}$$

9. SIMULATION OF LEACH AND LEACH-SM

There are three ways to estimate WSN lifetime: analytically, by simulation or by measurements in an actually deployed network. It is impossible to provide general analytical formulas for calculating the WSN's lifetime, because they depend in a complex way on many random variables. The cost of actually deploying the network, just for the purpose of testing, is extremely high. Therefore, the only feasible way of estimating WSN lifetime for LEACH and LEACH-SM is simulation. Such simulation, produced with MATLAB, is the topic of this chapter.

The special-case (as opposed to general) formulas for WSN lifetime, residual WSN lifetime, and the number of frames per round for LEACH and LEACH-SM, derived in the previous section, are complemented in this Chapter with more general simulations results produced by MATLAB. The simulations allow to compare WSN lifetimes for LEACH and LEACH-SM. We also show that WSN lifetime for LEACH-SM be extended with the replacements of exhausted primary nodes (either the original primaries, or spares that became primaries) by spare sensor nodes.

9.1 Simulation Description

We are measuring WSN lifetime by simulating the behavior of a single node. We study the impact of spares, and duration of the nap interval of cluster head on the WSN lifetime. We generate results based on different executions representing different scenarios. They are described in Section 9.1.1.

In order to compare two protocols and find out which one is better based on WSN lifetime, it is important to have good energy consumption model. Section 9.1.2 presents energy consumption model for single sensor node.

9.1.1 Simulation Scenarios

In this simulation we are evaluating performance of two protocols (LEACH and LEACH-SM) in terms of their WSN lifetime (which is a direct consequence of their energy consumption). In the first part of the simulation experiments (reported in Subsection 9.5.1), we consider scenarios without spares, comparing the two protocols. The comparison is possible since both protocols can function without spares. In the second part of the simulation experiments (reported in Subsection 9.5.1.2), we consider scenarios with spares. We can investigate only performance of the LEACH-SM protocol since LEACH does not work with spares (thus for these experiments there are no simulation results for LEACH).

We consider a static network of 100 sensor nodes, and assume a fixed number of clusters in each round for both protocols. This number of clusters is calculated using our model for the number of frames per round (Subsection 9.1.2.2).

We investigate the WSN lifetime against the duration of the nap interval for the cluster head (σ^{CH}) and against the spare ratio, i.e. the ratio of the cluster nodes that become spares (α). In this simulation, we consider the range value $\sigma^{CH} = 0, 10, 20, 30$ for the duration of nap interval for the cluster head, and the value range $\alpha = 25\%, 50\%$ for of the spare ratio.

Whenever possible we used for our scenarios the same input parameters as given in Reference [Hein00].

We record simulation results for as single node with combinations of values for σ^{CH} and α for 20 simulation runs as shown in Table 9.1.

Table 9.1. Simulated combinations of values for σ^{CH} and α.

Duration of the nap interval for the cluster head (σ^{CH})	Spare Ratio (α)	Number of simulation runs
0	25%	20
0	50%	20
10	25%	20
10	50%	20
20	25%	20
20	50%	20
30	25%	20
30	50%	20

Based on 20 simulation runs for a single node, we obtained 20 *individual* energy consumption curves, and 20 *individual* WSN lifetimes for each simulated node (i.e., the points where these curves have the energy value equal zero, i.e. where the curves touch the 0 x axis). Then, we calculate the *average* energy consumption curve and find from them the *average* WSN lifetime for a single node.

Note that both LEACH and LEACH-SM use well-planned rotations of the cluster head role among all the cluster nodes, and ensure that all nodes serve as the cluster head exactly once during WSN lifetime. This implies that almost all sensor nodes die (due to energy exhaustion at the same time. Thus, WSN lifetime is approximately equal to the lifetime of each single sensor node in LEACH as well as in LEACH-SM if spare replacement in the latter is not allowed.

9.1.2 Simulation Models

In order to compare two protocols (LEACH and LEACH-SM) based on WSN lifetime, it is important to have good energy consumption model. The accuracy of estimated results depends on selected simulation parameters such as knowing time spent by each node in each state, as well as the current drawn by the node circuitry in each state.

9.1.2.1 Energy Consumption Model

The energy consumption by a node includes: (i) energy consumption during sensing and logging (incl. energy consumed by the onboard sensors), (ii) energy consumption during sending and receiving data. In our analysis we ignore small amounts of energy needed: (i) by regular nodes to receive rare and short messages from their cluster heads; and (ii) by cluster heads to send these messages to regular nodes.

9.1.2.2 Model for Number of Frames Per Round

The number of frames per round is an optimization parameter for WSN lifetime in LEACH and LEACH-SM. Finding frames is the most complex part of measuring WSN lifetime. Therefore, by using Equation (5.19), we calculated the optimal number of frames per round for LEACH and LEACH-SM as:

$$F = \left\lfloor \frac{3600 \times B_{cap}[Ah] - (I^{Setup} \times \tau^{Setup} \times R)}{(I^{CH} \times \tau^{CH}) + I^{Reg} \times \tau^{Reg} \times (R-1)} \right\rfloor$$

where

B_{cap}: Capacity of a sensor node battery

I^{Setup}: Average current drawn by a node during the setup phase

τ^{Setup}: Average duration of setup phase

I^{CH}: Average current drawn by a cluster head for the Awake interval

τ^{CH}: Duration of the Awake interval of a cluster head

τ^{Reg}: Duration of the Awake interval of a regular node

I^{Reg}: Average current drawn by a regular node during the Awake interval

R : Number of rounds

9.2 Metrics

The following quantities are measured by the simulation:

a) Average lifetime of cluster heads

b) Average lifetime of regular nodes

c) Average lifetime of spares

d) Average lifetime of WSN

9.3 Simulation Assumptions

We use the following basic assumptions for the simulation:

a) Number of clusters is fixed

b) The numbers of nodes in each cluster is fixed

c) When a spare is used to replace an exhausted node, the spare becomes a cluster head (it becomes a regular node after serving as cluster head for 1 round).

9.4 Simulation Setup

We ran WSN simulations using MATLAB to estimate WSN lifetime for LEACH and LEACH-SM. We consider 100 randomly deployed sensor nodes. For communication we assume channel bandwidth was set to 1 Mbps. Averages are calculated over 20 simulation runs. The remaining parameters are summarized in Table 9.2 and Table 9.3.

9.4.1 Input Parameters

Table 9.2 shows the input parameters for plotting and their values. (Some of the values were used as simulation parameters for LEACH; cf. Section 4 in [Hein00]).

Table 9.2. Input parameters.

Variable	**Value**	**Description**
N	100	Number of nodes
l	4000 [bits]	Data packet size without header
$l^* - l$	200 [bits]	Data packet header size
$\tau_{sen+log}^{Reg}$	7.8125×10^{-5}[sec]	Time taken by a regular sensor node for sensing and logging the sensed data
τ_{snd}^{Reg}	1.00×10^{-6}[sec]	Time taken by a regular node for sending 1 bit of data to its cluster head
$I_{sen+log}^{Reg}$	0.0096 [A]	Average current drawn by a regular sensor node for sensing and logging the sensed data
I_{snd}^{Reg}	0.018 [A]	Average current drawn by a regular node for sending data to its cluster head
I^{Setup}	15 [A]	Average current drawn by a node during the setup phase
I_{agg}^{CH}	0.0508 [A]	Average current drawn by the cluster head during aggregation of the received data in LEACH / LEACH-SM

Table 9.2 – Continued

I_{snd}^{CH}	0.088 [A]	Average current drawn by a cluster head for sending data
$\tau_{rcv+log}^{CH}$	1.00×10^{-6}[sec]	Time taken by a cluster head for receiving and logging the data
$\bar{\bar{I}}^{SS}$	15 [A]	Average current drawn by a node during the setup phase in LEACH-SM
$\bar{\bar{\tau}}^{SS}$	10 [sec]	Duration of the spare selection interval in LEACH-SM
$I_{rcv+log}^{CH}$	0.096 [A]	Average current drawn by the cluster head during receiving data from regular sensor nodes
B_{cap}	5 [Ah]	Capacity of a sensor node battery
r	1 [Mbps]	Average data transmission rate from a regular node to its cluster head or from a cluster head to a base station in LEACH/LEACH-SM
τ_{agg}^{CH} / $\bar{\bar{\tau}}_{agg}^{CH}$	0.3125 [s]	Average time taken by a cluster head for aggregation of data received from its regular nodes in LEACH/LEACH-SM
τ_{snd}^{CH}	1.00×10^{-6}[sec]	Time taken by a cluster head for sending 1 bit of data to its cluster head

9.4.2 Random Variables

As mentioned, we are using the same simulation parameters as used in LEACH [Hein00] whenever possible because in this way we will able to compare both protocols (LEACH and LEACH-SM) based on WSN lifetime to the original output simulation values given by [Hein00]. However, we are using our energy consumption model. Our energy consumption model is more detailed than the model given in [Hein00] because we also consider the energy consumed in the process of sampling, processing and logging data by a sensor node.

The sensor node components primarily contributing to the overall energy consumption are: the on board sensors, the analog-to-digital converter unit (ADC), the micro controller, and the communication module (including the sending and receiving modules. Energy consumed in the process of sampling, processing and logging data by a sensor node is comparable to the energy consumed by the sender and receiver circuits of the sensor node. To run all components, the Microcontroller needs be Awake all the time.

Energy consumption by a node includes: (i) energy consumption during sensing and logging (incl. energy consumed by the onboard sensors), (ii) energy consumption during sending and receiving data. Table 9.3 lists and describes random variables and their distributions.

Table 9.3. Random variables and their statistical properties.

Random Variable	Value Range	Statistical Distribution	Description
α	$0 \leq \alpha < 100$	Uniform distribution	The spare ratio(s) for LEACH-SM
σ^{CH}	$0 \leq \sigma^{CH}$	Uniform distribution	Duration of a Nap interval of a cluster head
τ^{CH}	$5.0572 \leq \tau^{CH} \leq 7.0572$	Uniform distribution	Duration of the Awake interval of a cluster head in LEACH
$\bar{\bar{\tau}}^{CH}$	$5.0572 \leq \bar{\bar{\tau}}^{CH} \leq 7.0572$	Uniform distribution	Duration of the Awake interval of a cluster head in LEACH-SM
τ^{Setup}/ $\bar{\bar{\tau}}^{Setup}$	$29 \leq \tau^{Setup} \leq 31$	Uniform distribution	Duration of the setup interval in LEACH / LEACH-SM
β	$0 \leq \beta < 100$	Uniform distribution	Data aggregation ratio
τ^{Reg}	$0.2167 \leq \tau^{Reg} \leq 0.4167$	Uniform distribution	Duration of the Awake interval of a regular node in LEACH

Table 9.3 – Continued

$\bar{\bar{\tau}}^{Reg}$	$0.2167 \leq \bar{\bar{\tau}}^{Reg} \leq 0.4167$	Uniform distribution	Duration of the Awake interval of a regular node in LEACH-SM

9.5 Simulation Results

This section presents simulation comparison of LEACH-SM with LEACH. MATLAB was used for the plotting the graphs.

Only two of the eight random variables from Table 9.3 are used as "control variables" that are investigated by producing plots of energy consumption and WSN lifetime against their values. These variables are: σ^{CH} (duration of a nap interval for a cluster head) and α (spare ratio, i.e., the ratio of the cluster nodes that become spares).

The spare ratio α and duration of the nap interval of cluster heads σ^{CH} were selected because they express the main differences between LEACH and LEACH-SM. The spare ratio characterizes the use of the spare nodes in LEACH-SM (with no spares in LEACH). Duration of the nap interval of cluster heads characterizes different workloads ("duty cycles") of cluster heads in LEACH and LEACH-SM.

9.5.1 Results of Energy Consumption and WSN Lifetime Simulations for LEACH and LEACH-SM without Spare Replacements

This section presents the results of energy consumption and WSN lifetime simulations for LEACH and LEACH-SM without using the spare replacement processes. The first subsection shows simulation results for individual combinations of values for

σ^{CH} (duration of a nap interval for a cluster head) and α (spare ratio), while the second subsection shows simulation results for ranges of σ^{CH} or α values.

9.5.1.1 Simulation Results for Individual Combinations of σ^{CH} and α Values

We consider here 8 cases with different combinations of values for σ^{CH} (duration of a nap interval for a cluster head) and α (spare ratio)—as shown in Table 9.4.

Case 1: $\sigma^{CH} = 0$ and $\alpha = 25\%$

Figure 9.1 shows twenty individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 25\%$. Table A.1 and Table A.2 in Appendix A give the detailed numerical results for these results of 20 simulation runs.

Table 9.4. Comparison of LEACH-SM with LEACH.

Case Number	**Duration of a nap interval for a cluster head (σ^{CH})**	**The spare ratio(s) for LEACH-SM (α)**	**Figures**	**Tables**
1.	0	25%	Figure 9.1 Figure 9.2	Table A.1 Table A.2
2.	0	50%	Figure 9.3 Figure 9.4	Table A.3 Table A.4

Table 5.1 – Continued

3.	10	25%	Figure 9.5 Figure 9.6	Table A.5 Table A.6
4.	10	50%	Figure 9.7 Figure 9.8	Table A.7 Table A.8
5.	20	25%	Figure 9.9 Figure 9.10	Table A.9 Table A.10
6.	20	50%	Figure 9.11 Figure 9.12	Table A.11 Table A.12
7.	30	25%	Figure 9.13 Figure 9.14	Table A.13 Table A.14
8.	30	50%	Figure 9.15 Figure 9.16	Table A.15 Table A.16

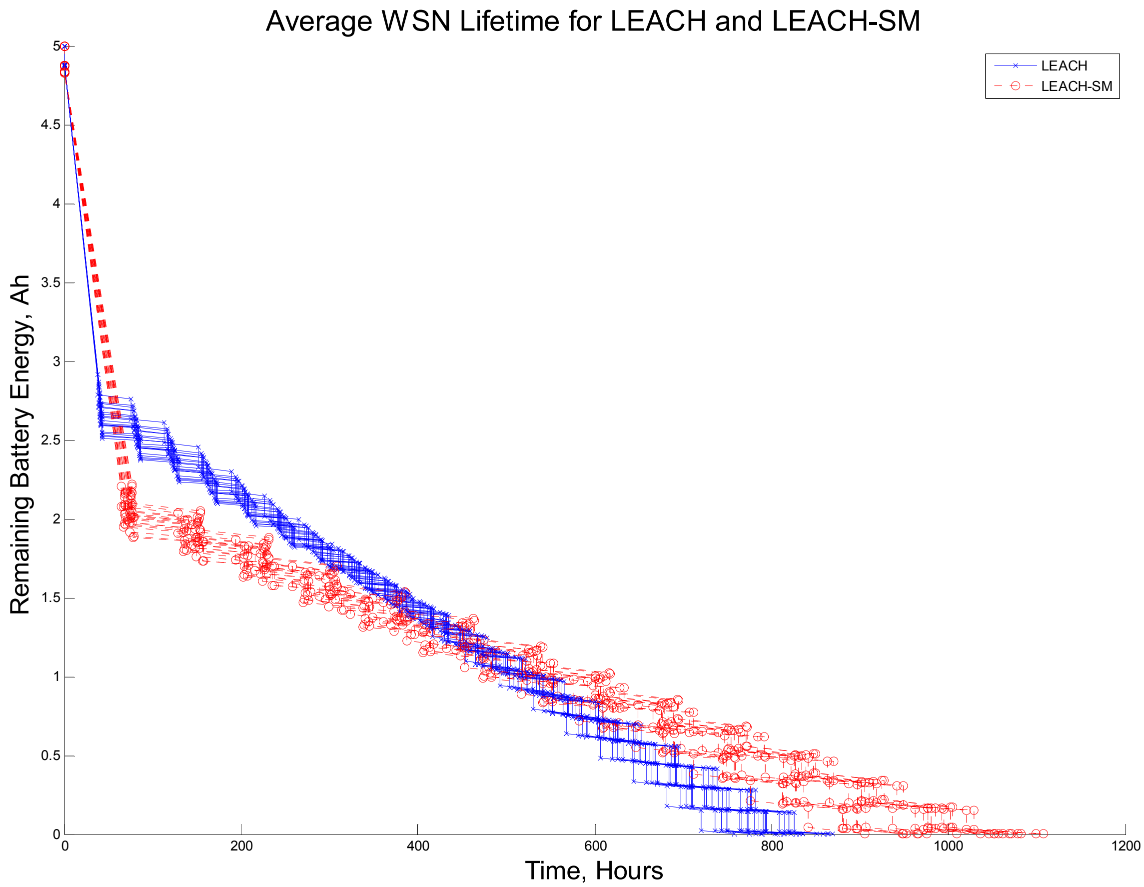


Figure 9.1. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH and for LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 25\%$ (based on 20 simulation runs).

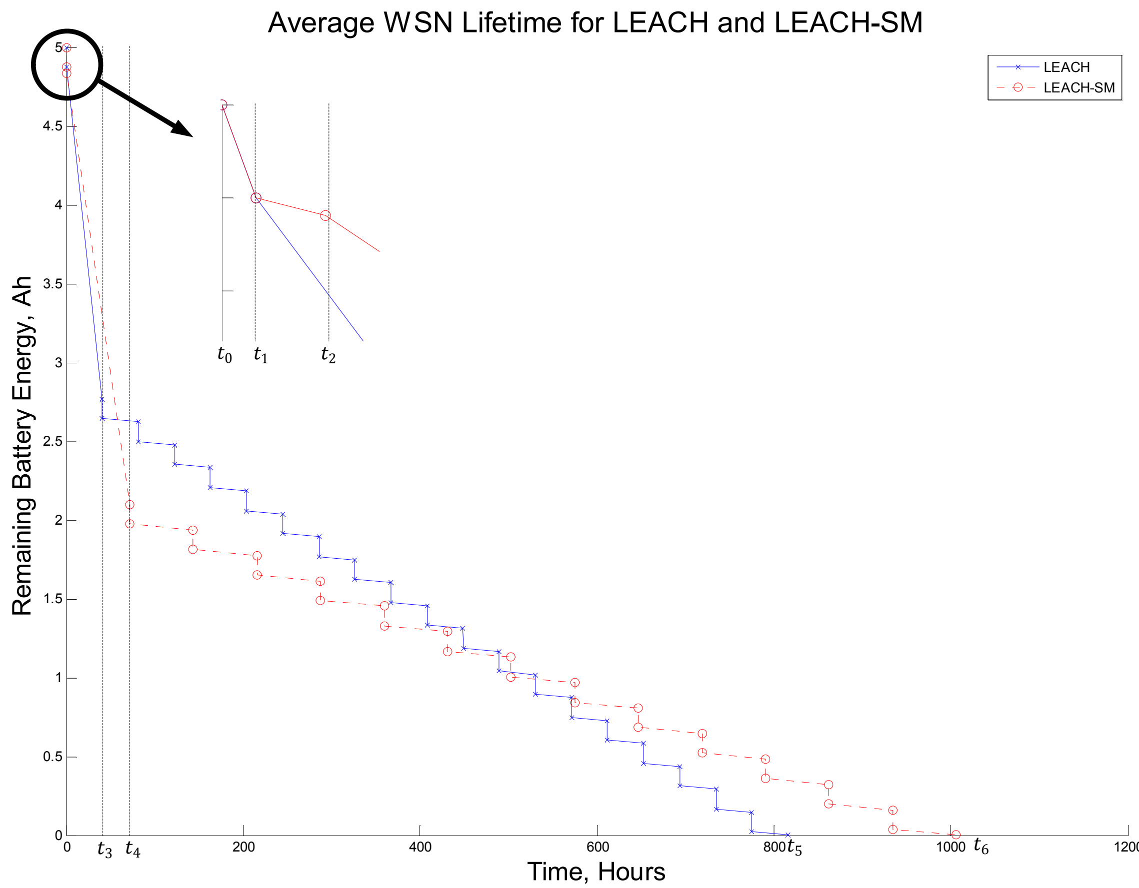


Figure 9.2. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 25\%$ (based on 20 simulation runs).

In both protocols, each node serves as a cluster head only once in its lifetime. This period of cluster head service corresponds to the steepest (initial) segment of each energy consumption curve.

The range of WSN lifetimes for LEACH is from 743 h to 855 h, and the range of WSN lifetimes for LEACH-SM is from 900 h to 1100 h. This means that the *worst* case of WSN lifetime for LEACH-SM is 6% better than the *best* case of WSN lifetime for

LEACH. However, the *best* case of WSN lifetime for LEACH-SM is 29% better than the *best* case of WSN lifetime for LEACH.

Figure 9.2 shows energy consumption curves and average WSN lifetime for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 25\%$. For LEACH, $[0, t_1]$ is the setup interval for a selected node in LEACH, $[t_1, t_3]$ is the interval when the node serves as a cluster head in LEACH, and $[t_3, t_5]$ is the interval when the node serves as a primary in LEACH. For LEACH-SM, $[t_0, t_1]$ is the setup interval for a selected node, $[t_1, t_2]$ is the spare selection phase, $[t_2, t_4]$ is the interval when the node serves as a cluster head, and $[t_3, t_5]$ is the interval when the node serves as a primary. (Line fragments parallel to the time axis indicate the nap periods—with no energy consumption.)

Figure 9.2 shows that a WSN in LEACH-SM can achieve lifetime longer than the same WSN in LEACH. For the simulated runs, WSN lifetime in LEACH-SM was longer about 23%.

Case 2: $\sigma^{CH} = 0$ and $\alpha = 50\%$

Figure 9.3 shows twenty individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 50\%$. Table A.3 and Table A.4 in Appendix A give the detailed numerical results for these results of 20 simulation runs.

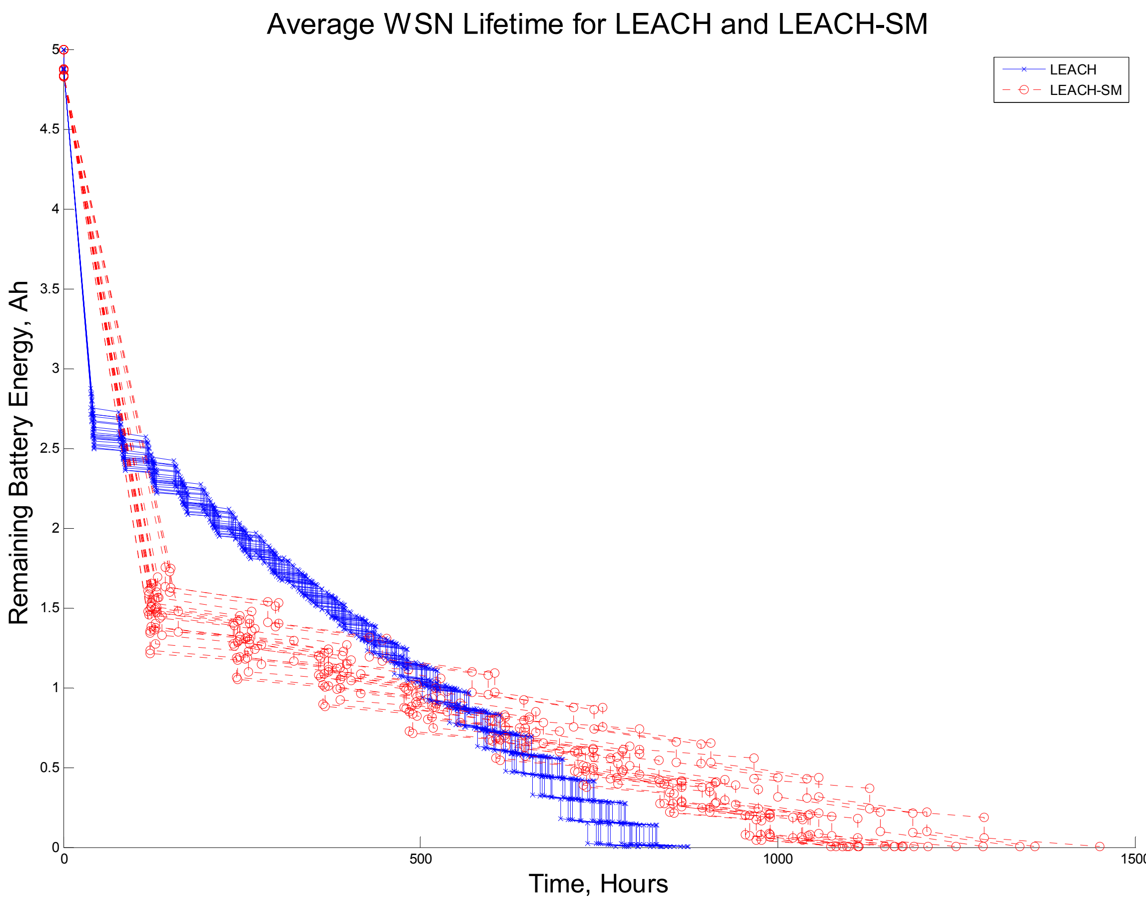


Figure 9.3. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH and for LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 50\%$ (based on 20 simulation runs).

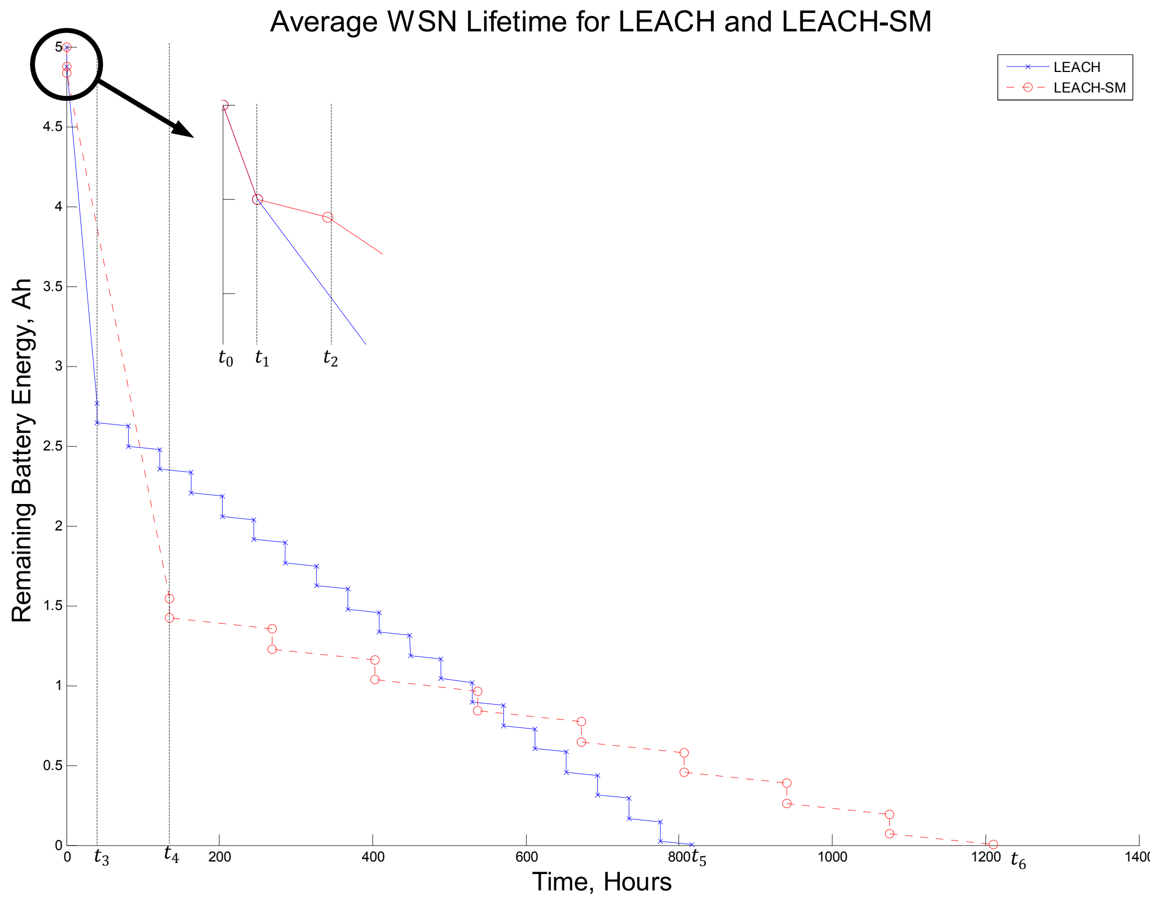


Figure 9.4. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 50\%$ (based on 20 simulation runs).

In both protocols, each node serves as a cluster head only once in its lifetime. This period of cluster head service corresponds to the steepest (initial) segment of each energy consumption curve.

The range of WSN lifetimes for LEACH is from 740 h to 850 h, and the range of WSN lifetimes for LEACH-SM is from 1100 h to 1300 h. This means that the *worst* case of WSN lifetime for LEACH-SM is 29% better than the *best* case of WSN lifetime for

LEACH. However, the *best* case of WSN lifetime for LEACH-SM is 52% better than the *best* case of WSN lifetime for LEACH.

Figure 9.4 shows energy consumption curves and average WSN lifetime for a single node in LEACH and LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 50\%$. For LEACH, $[0, t_1]$ is the setup interval for a selected node in LEACH, $[t_1, t_3]$ is the interval when the node serves as a cluster head in LEACH, and $[t_3, t_5]$ is the interval when the node serves as a primary in LEACH. For LEACH-SM, $[t_0, t_1]$ is the setup interval for a selected node, $[t_1, t_2]$ is the spare selection phase, $[t_2, t_4]$ is the interval when the node serves as a cluster head, and $[t_3, t_5]$ is the interval when the node serves as a primary. (Line fragments parallel to the time axis indicate the nap periods—with no energy consumption.)

Figure 9.4 shows that a WSN in LEACH-SM can achieve lifetime longer than the same WSN in LEACH. For the simulated runs, WSN lifetime in LEACH-SM was longer about 48%.

Case 3: $\sigma^{CH} = 10$ and $\alpha = 25\%$

Figure 9.5 shows twenty individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 25\%$. Table A.5 and Table A.6 in Appendix A give the detailed numerical results for these results of 20 simulation runs.

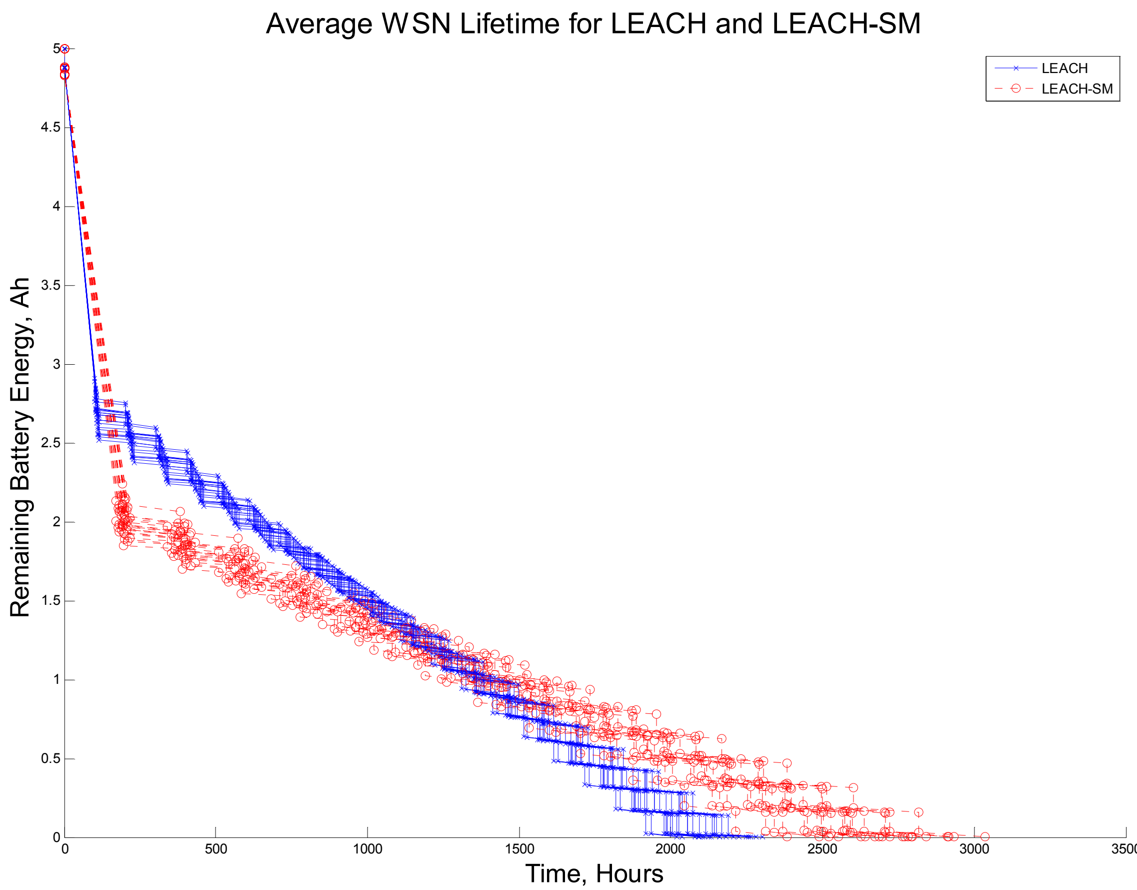


Figure 9.5. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH and for LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 25\%$ (based on 20 simulation runs).

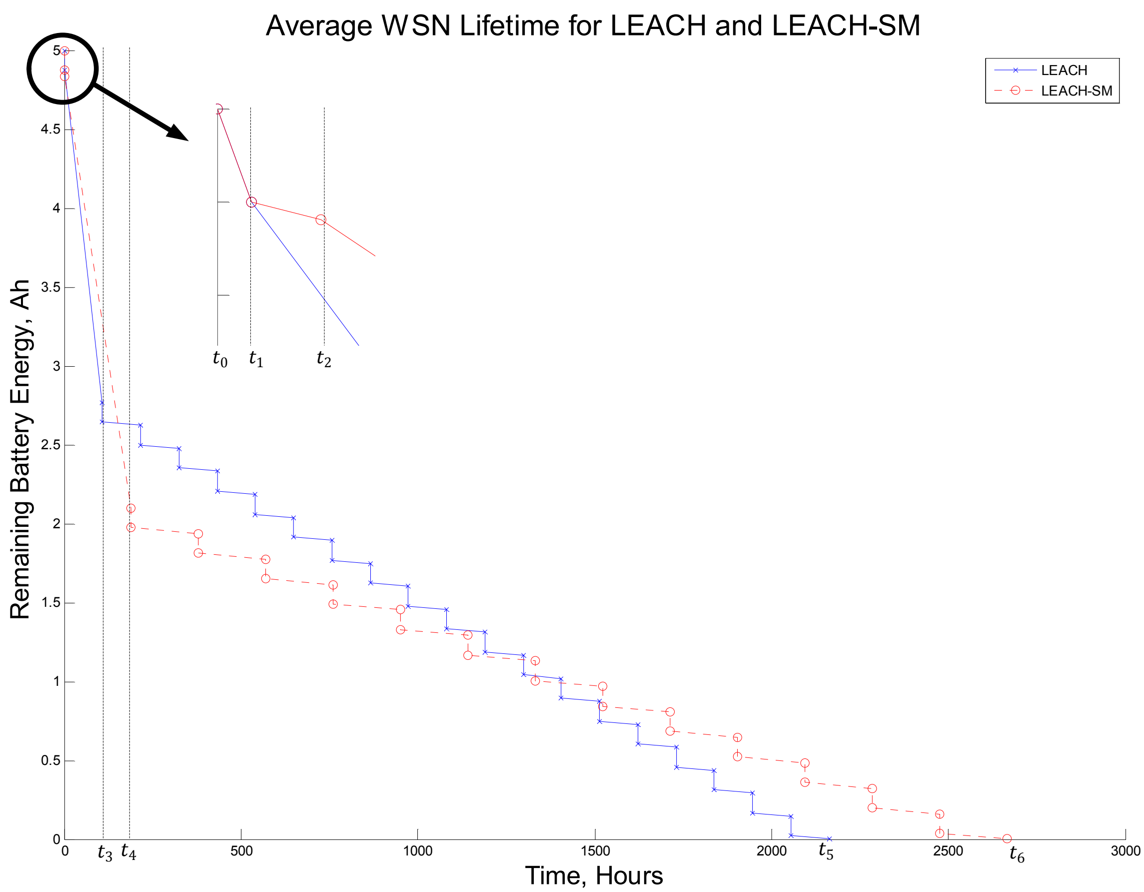


Figure 9.6. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 25\%$ (based on 20 simulation runs).

In both protocols, each node serves as a cluster head only once in its lifetime. This period of cluster head service corresponds to the steepest (initial) segment of each energy consumption curve.

The range of WSN lifetimes for LEACH is from 2062 h to 2362 h, and the range of WSN lifetimes for LEACH-SM is from 2569 h to 2769 h. This means that the *worst* case of WSN lifetime for LEACH-SM is 8% better than the *best* case of WSN lifetime

for LEACH. However, the *best* case of WSN lifetime for LEACH-SM is 17% better than the *best* case of WSN lifetime for LEACH.

Figure 9.6 shows energy consumption curves and average WSN lifetime for a single node in LEACH and LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 25\%$. For LEACH, $[0, t_1]$ is the setup interval for a selected node in LEACH, $[t_1, t_3]$ is the interval when the node serves as a cluster head in LEACH, and $[t_3, t_5]$ is the interval when the node serves as a primary in LEACH. For LEACH-SM, $[t_0, t_1]$ is the setup interval for a selected node, $[t_1, t_2]$ is the spare selection phase, $[t_2, t_4]$ is the interval when the node serves as a cluster head, and $[t_3, t_5]$ is the interval when the node serves as a primary. (Line fragments parallel to the time axis indicate the nap periods—with no energy consumption.)

Figure 9.6 shows that a WSN in LEACH-SM can achieve lifetime longer than the same WSN in LEACH. For the simulated runs, WSN lifetime in LEACH-SM was longer about 23%.

Case 4: $\sigma^{CH} = 10$ and $\alpha = 50\%$

Figure 9.7 shows twenty individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 50\%$. Table A.7 and Table A.8 in Appendix A give the detailed numerical results for these results of 20 simulation runs.

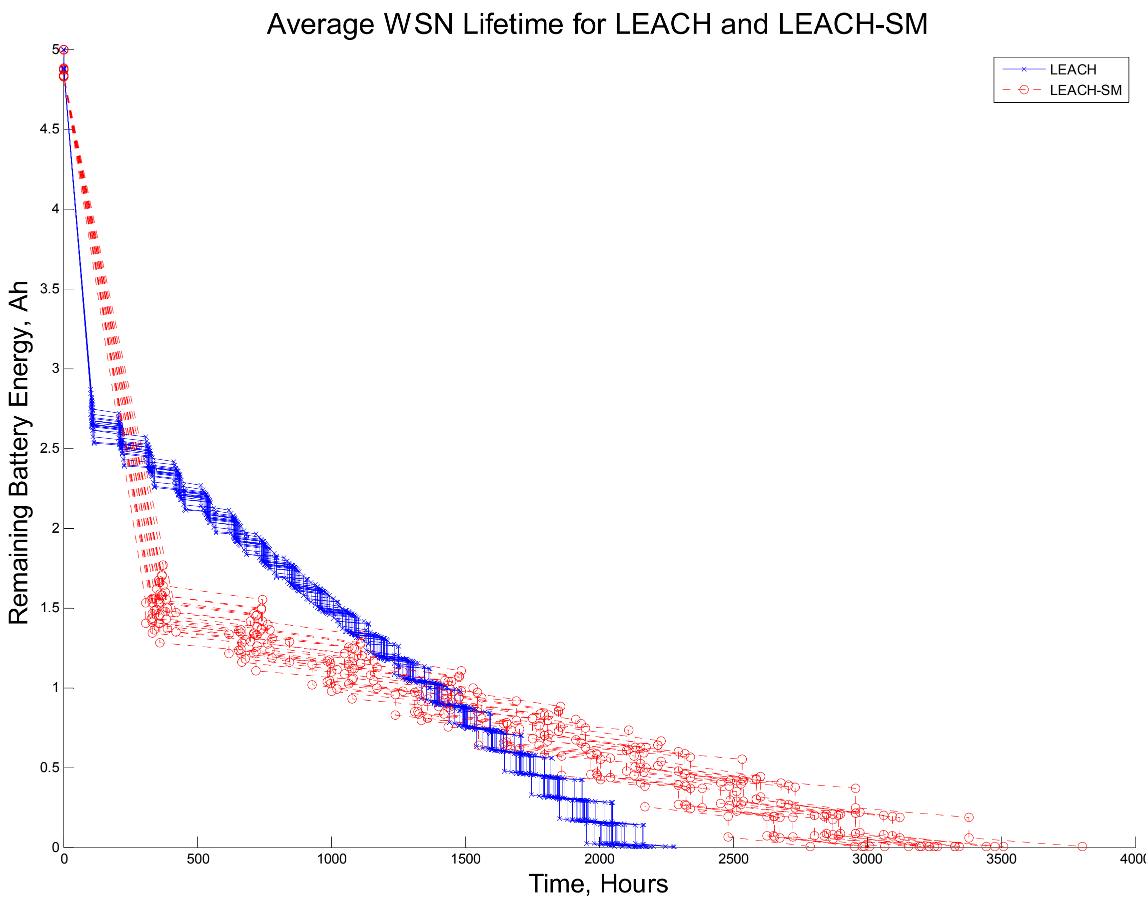


Figure 9.7. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH and for LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 50\%$ (based on 20 simulation runs).

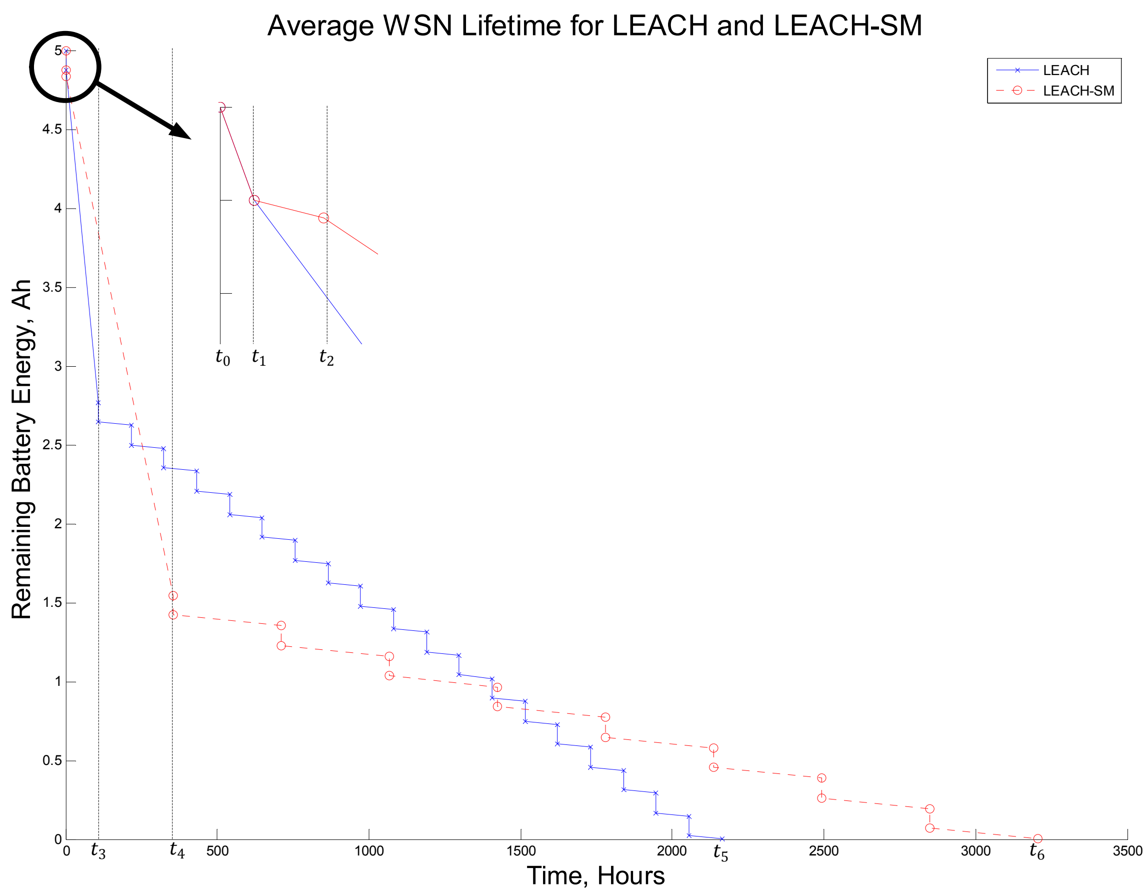


Figure 9.8. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 50\%$ (based on 20 simulation runs).

In both protocols, each node serves as a cluster head only once in its lifetime. This period of cluster head service corresponds to the steepest (initial) segment of each energy consumption curve.

The range of WSN lifetimes for LEACH is from 2062 h to 2362 h, and the range of WSN lifetimes for LEACH-SM is from 3106 h to 3306 h. This means that the *worst* case of WSN lifetime for LEACH-SM is 31% better than the *best* case of WSN lifetime

for LEACH. However, the *best* case of WSN lifetime for LEACH-SM is 40% better than the *best* case of WSN lifetime for LEACH.

Figure 9.8 shows energy consumption curves and average WSN lifetime for a single node in LEACH and LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 50\%$. For LEACH, $[0, t_1]$ is the setup interval for a selected node in LEACH, $[t_1, t_3]$ is the interval when the node serves as a cluster head in LEACH, and $[t_3, t_5]$ is the interval when the node serves as a primary in LEACH. For LEACH-SM, $[t_0, t_1]$ is the setup interval for a selected node, $[t_1, t_2]$ is the spare selection phase, $[t_2, t_4]$ is the interval when the node serves as a cluster head, and $[t_3, t_5]$ is the interval when the node serves as a primary. (Line fragments parallel to the time axis indicate the nap periods—with no energy consumption.)

Figure 9.8 shows that a WSN in LEACH-SM can achieve lifetime longer than the same WSN in LEACH. For the simulated runs, WSN lifetime in LEACH-SM was longer about 48%.

Case 5: $\sigma^{CH} = 20$ and $\alpha = 25\%$

Figure 9.9 shows twenty individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 20$ and $\alpha = 25\%$. Table A.9 and Table A.10 in Appendix A give the detailed numerical results for these results of 20 simulation runs.

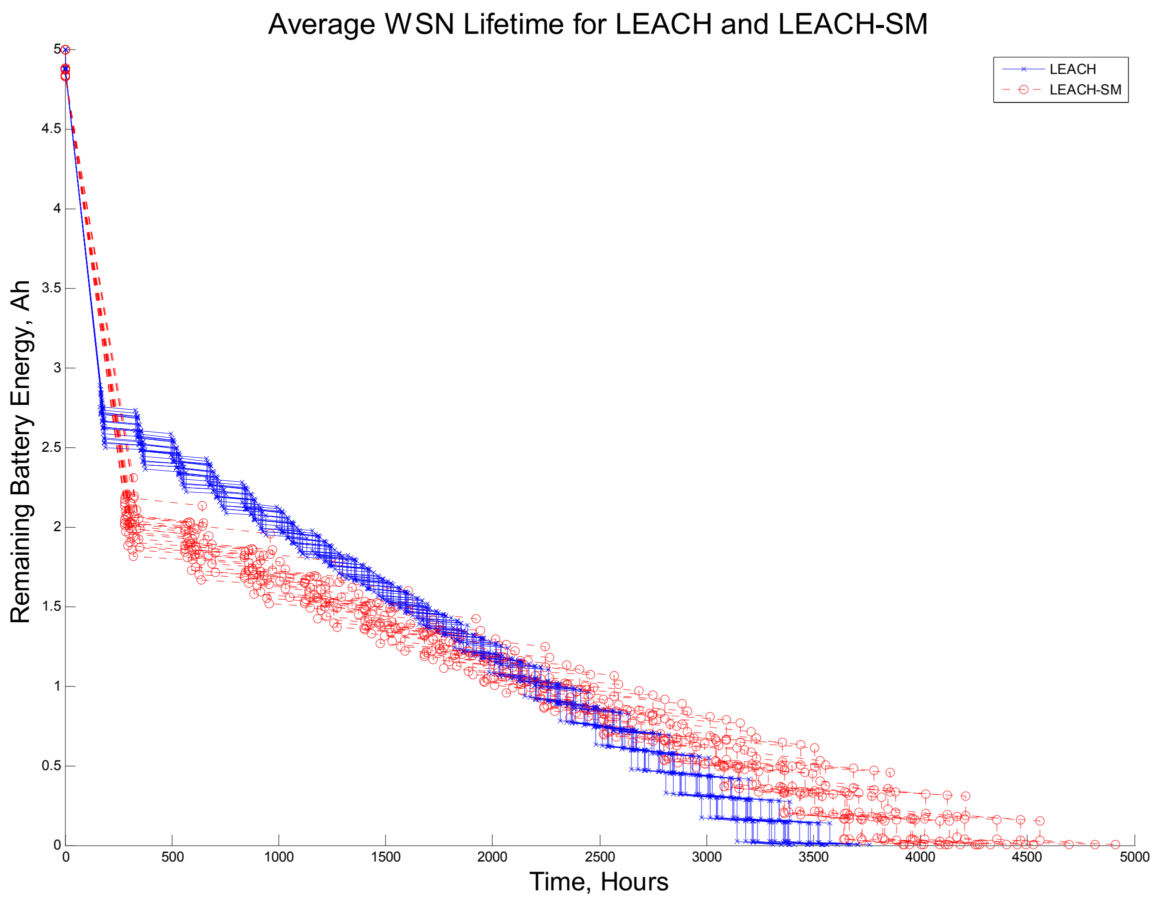


Figure 9.9. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH and for LEACH-SM with $\sigma^{CH} = 20$ and $\alpha = 25\%$ (based on 20 simulation runs).

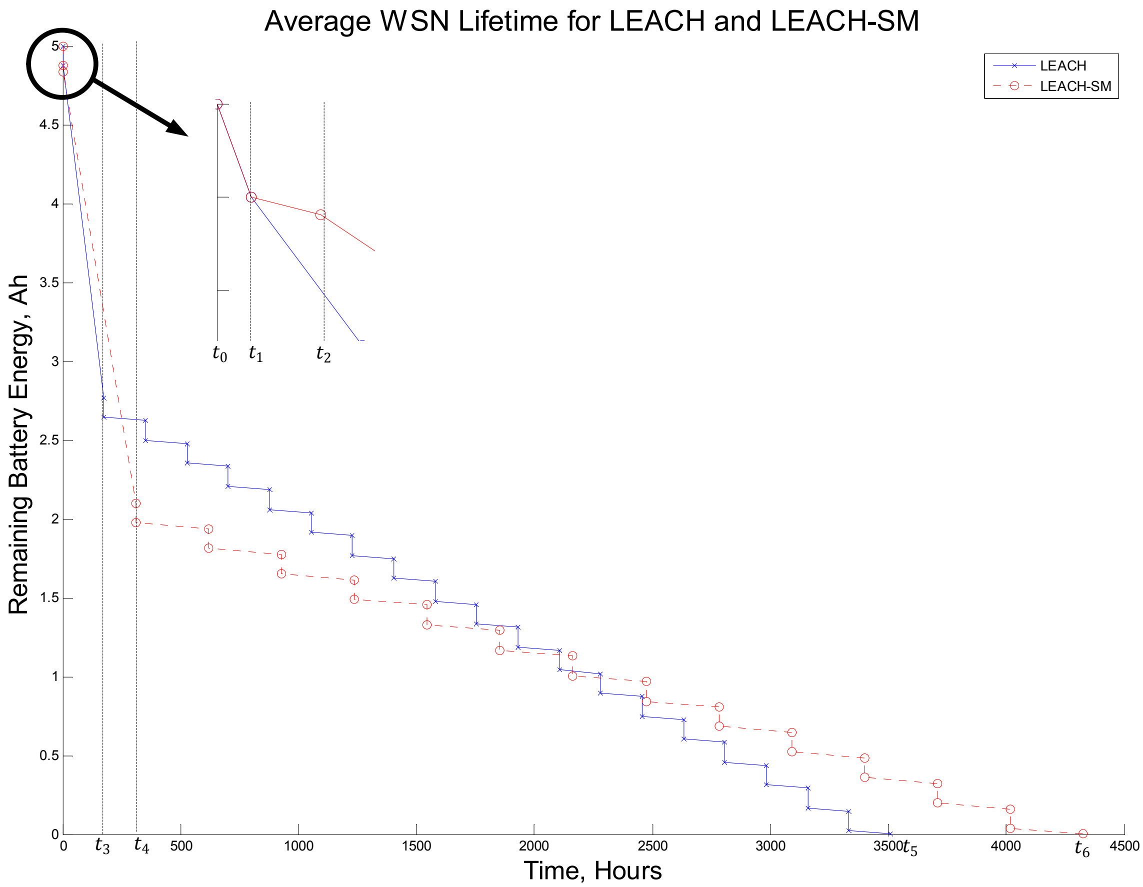


Figure 9.10. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 20$ and $\alpha = 25\%$ (based on 20 simulation runs).

In both protocols, each node serves as a cluster head only once in its lifetime. This period of cluster head service corresponds to the steepest (initial) segment of each energy consumption curve.

The range of WSN lifetimes for LEACH is from 3410 h to 3610 h, and the range of WSN lifetimes in LEACH-SM is from 4227 h to 4427 h. This means that the *worst* case of WSN lifetime for LEACH-SM is 17% better than the *best* case of WSN lifetime

for LEACH. However, the *best* case of WSN lifetime for LEACH-SM is 23% better than the *best* case of WSN lifetime for LEACH.

Figure 9.10 shows energy consumption curves and average WSN lifetime for a single node in LEACH and LEACH-SM with $\sigma^{CH} = 20$ and $\alpha = 25\%$. For LEACH, $[0, t_1]$ is the setup interval for a selected node in LEACH, $[t_1, t_3]$ is the interval when the node serves as a cluster head in LEACH, and $[t_3, t_5]$ is the interval when the node serves as a primary in LEACH. For LEACH-SM, $[t_0, t_1]$ is the setup interval for a selected node, $[t_1, t_2]$ is the spare selection phase, $[t_2, t_4]$ is the interval when the node serves as a cluster head, and $[t_3, t_5]$ is the interval when the node serves as a primary. (Line fragments parallel to the time axis indicate the nap periods—with no energy consumption.)

Figure 9.10 shows that a WSN in LEACH-SM can achieve lifetime longer than the same WSN in LEACH. For the simulated runs, WSN lifetime for LEACH-SM was longer about 23%.

Case 6: $\sigma^{CH} = 20$ and $\alpha = 50\%$

Figure 9.11 shows twenty individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 20$ and $\alpha = 50\%$. Table A.11 and Table A.12 in Appendix A give the detailed numerical results for these results of 20 simulation runs.

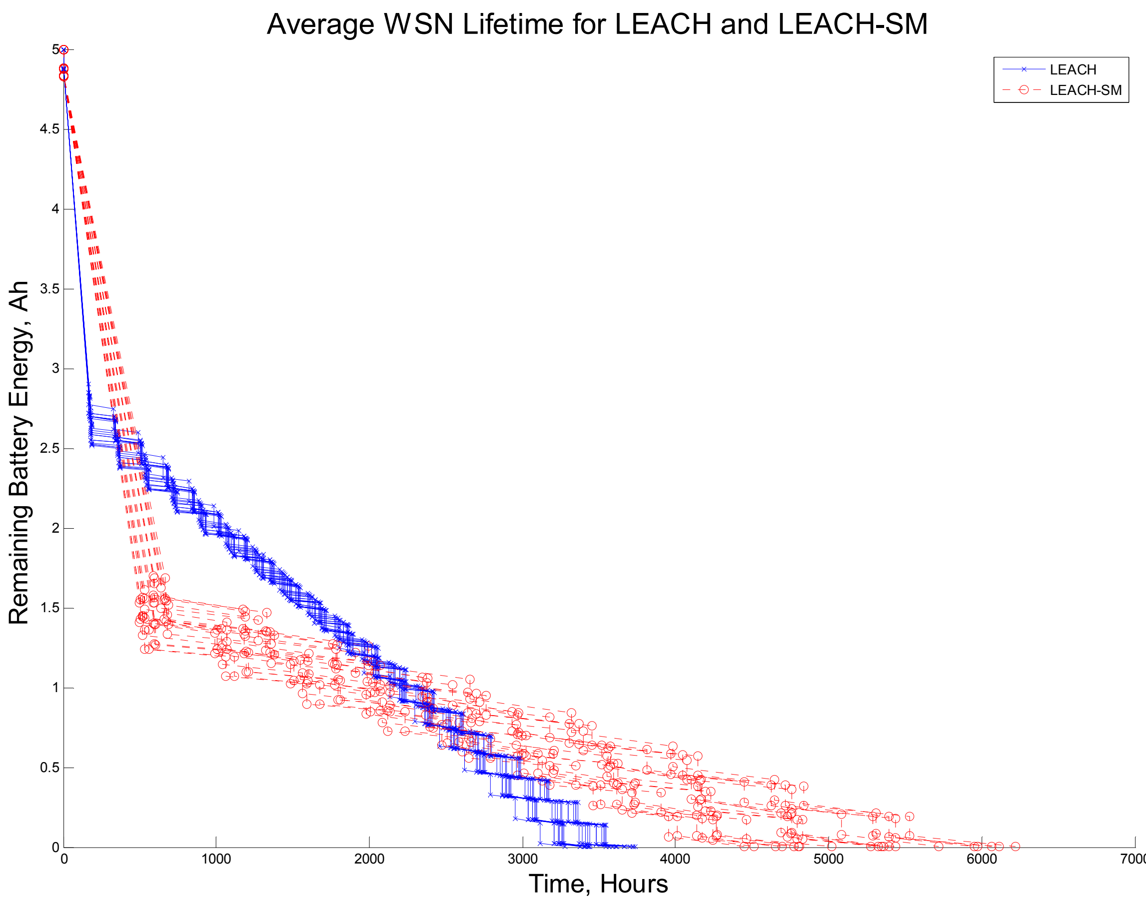


Figure 9.11. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH and for LEACH-SM with $\sigma^{CH} = 20$ and $\alpha = 50\%$ (based on 20 simulation runs).

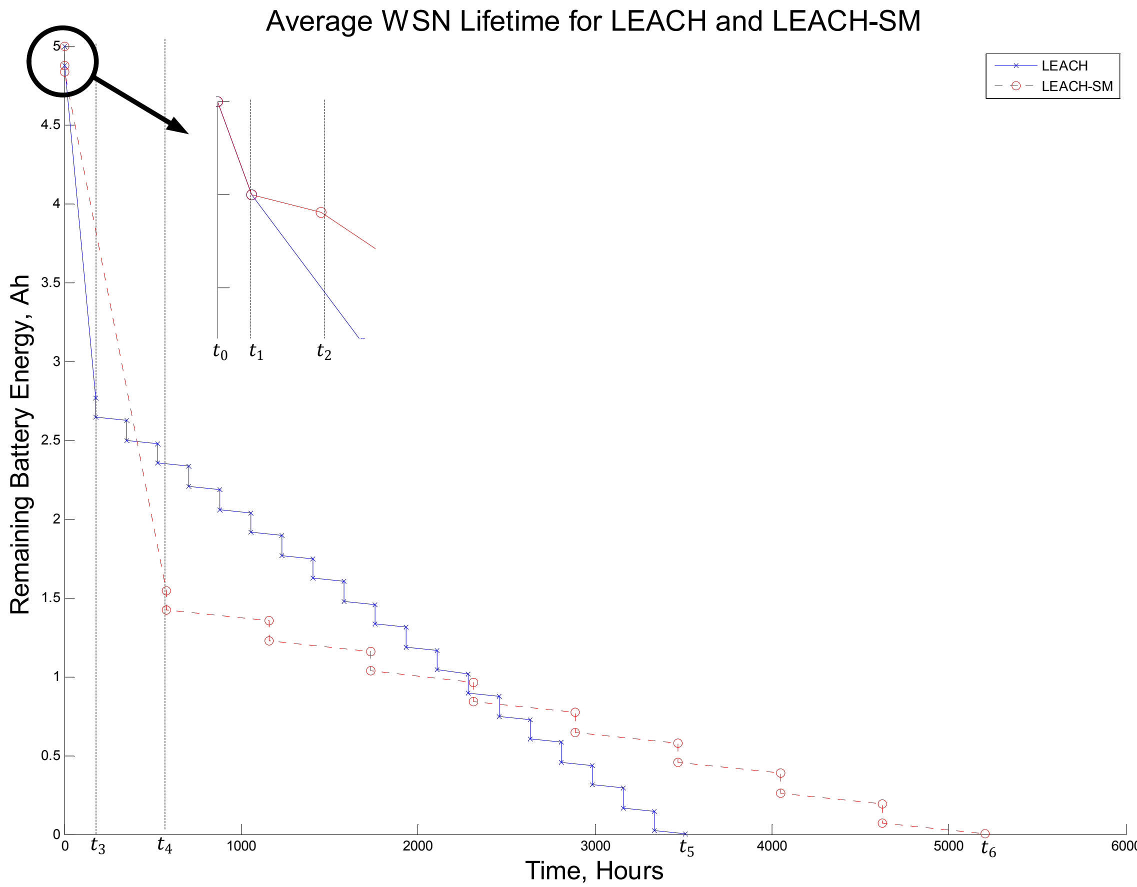


Figure 9.12. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 20$ and $\alpha = 50\%$ (based on 20 simulation runs).

In both protocols, each node serves as a cluster head only once in its lifetime. This period of cluster head service corresponds to the steepest (initial) segment of each energy consumption curve.

The range of WSN lifetimes for LEACH is from 3410 h to 3610 h, and the range of WSN lifetimes in LEACH-SM is from 5128 h to 5328 h. This means that the *worst* case of WSN lifetime for LEACH-SM is 42% better than the *best* case of WSN lifetime

for LEACH. However, the *best* case of WSN lifetime for LEACH-SM is 47% better than the *best* case of WSN lifetime for LEACH.

Figure 9.12 shows energy consumption curves and average WSN lifetime for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 20$ and $\alpha = 50\%$. For LEACH, $[0, t_1]$ is the setup interval for a selected node in LEACH, $[t_1, t_3]$ is the interval when the node serves as a cluster head in LEACH, and $[t_3, t_5]$ is the interval when the node serves as a primary in LEACH. For LEACH-SM, $[t_0, t_1]$ is the setup interval for a selected node, $[t_1, t_2]$ is the spare selection phase, $[t_2, t_4]$ is the interval when the node serves as a cluster head, and $[t_3, t_5]$ is the interval when the node serves as a primary. (Line fragments parallel to the time axis indicate the nap periods—with no energy consumption.)

Figure 9.12 shows that a WSN in LEACH-SM can achieve lifetime longer than the same WSN in LEACH. For the simulated runs, WSN lifetime in LEACH-SM was longer about 48%.

Case 7: $\sigma^{CH} = 30$ and $\alpha = 25\%$

Figure 9.13 shows twenty individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 25\%$. Table A.13 and Table A.14 in Appendix A give the detailed numerical results for these results of 20 simulation runs.

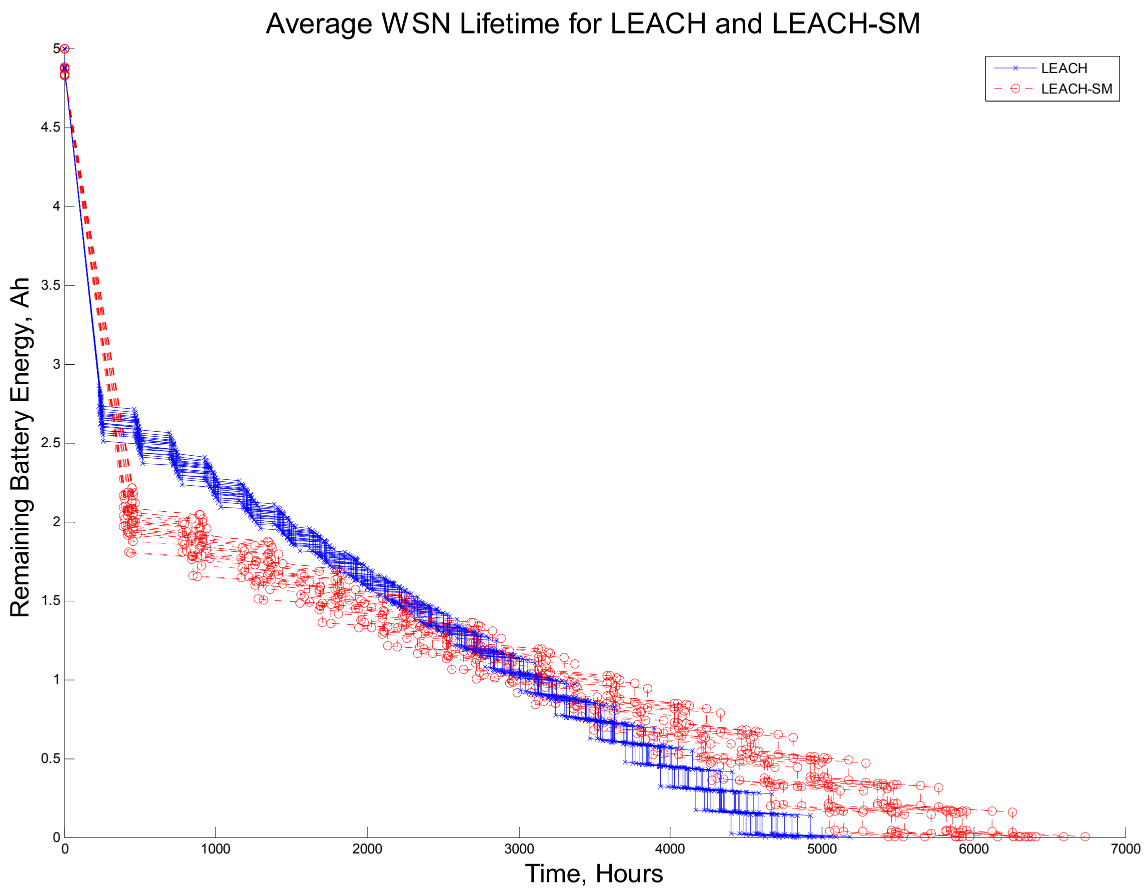


Figure 9.13. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH and for LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 25\%$ (based on 20 simulation runs).

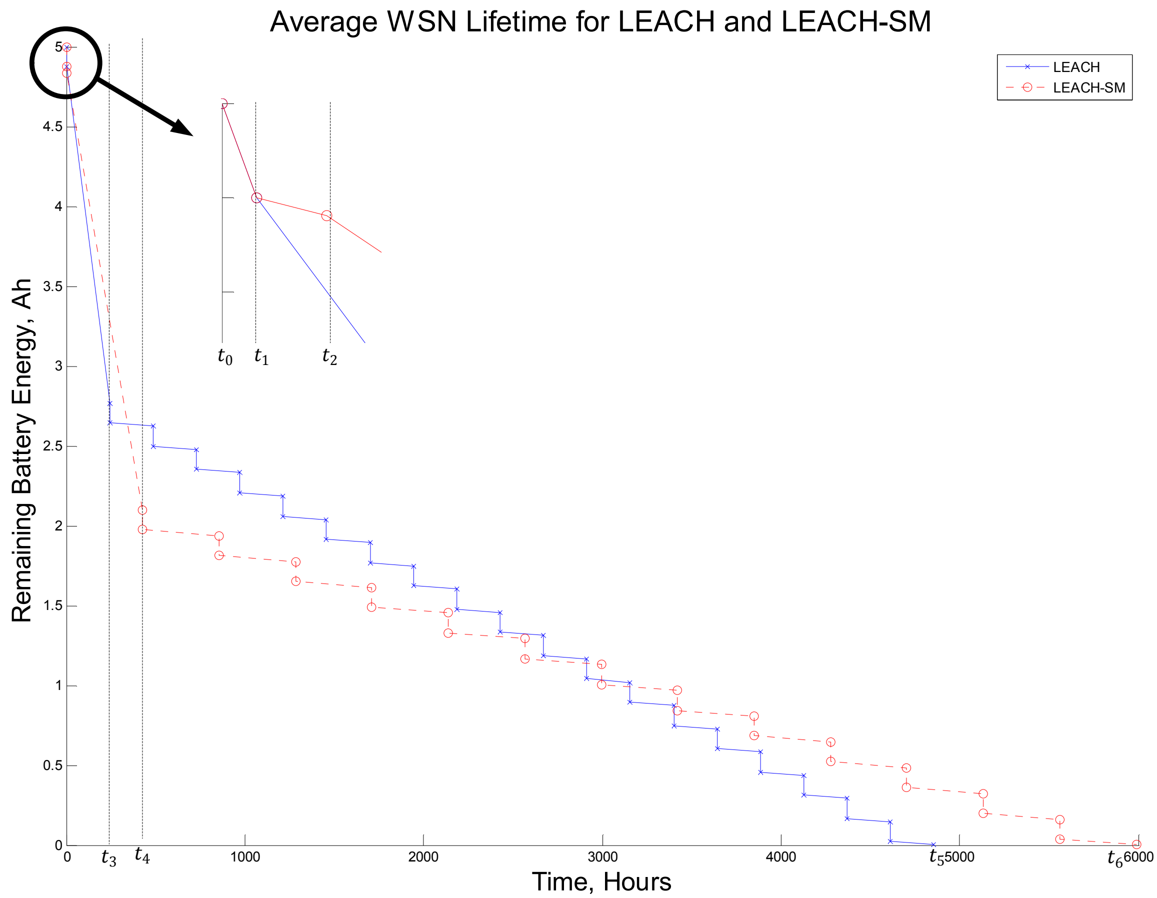


Figure 9.14. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 25\%$ (based on 20 simulation runs).

In both protocols, each node serves as a cluster head only once in its lifetime. This period of cluster head service corresponds to the steepest (initial) segment of each energy consumption curve.

The range of WSN lifetimes for LEACH is from 4756 h to 4956 h, and the range of WSN lifetimes in LEACH-SM is from 5888 h to 8088 h. This means that the *worst* case of WSN lifetime for LEACH-SM is 18% better than the *best* case of WSN lifetime for LEACH. However, the *best* case of WSN lifetime for LEACH-SM is 63% better than the *best* case of WSN lifetime for LEACH.

Figure 9.14 shows energy consumption curves and average WSN lifetime for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 25\%$. For LEACH, $[0, t_1]$ is the setup interval for a selected node in LEACH, $[t_1, t_3]$ is the interval when the node serves as a cluster head in LEACH, and $[t_3, t_5]$ is the interval when the node serves as a primary in LEACH. For LEACH-SM, $[t_0, t_1]$ is the setup interval for a selected node, $[t_1, t_2]$ is the spare selection phase, $[t_2, t_4]$ is the interval when the node serves as a cluster head, and $[t_3, t_5]$ is the interval when the node serves as a primary. (Line fragments parallel to the time axis indicate the nap periods—with no energy consumption.)

Figure 9.14 shows that a WSN in LEACH-SM can achieve lifetime longer than the same WSN in LEACH. For the simulated runs, WSN lifetime in LEACH-SM was longer about 23%.

Case 8: $\sigma^{CH} = 30$ and $\alpha = 50\%$

Figure 9.15 shows twenty individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 50\%$. Table A.15 and Table A.16 in Appendix A give the detailed numerical results for these results of 20 simulation runs.

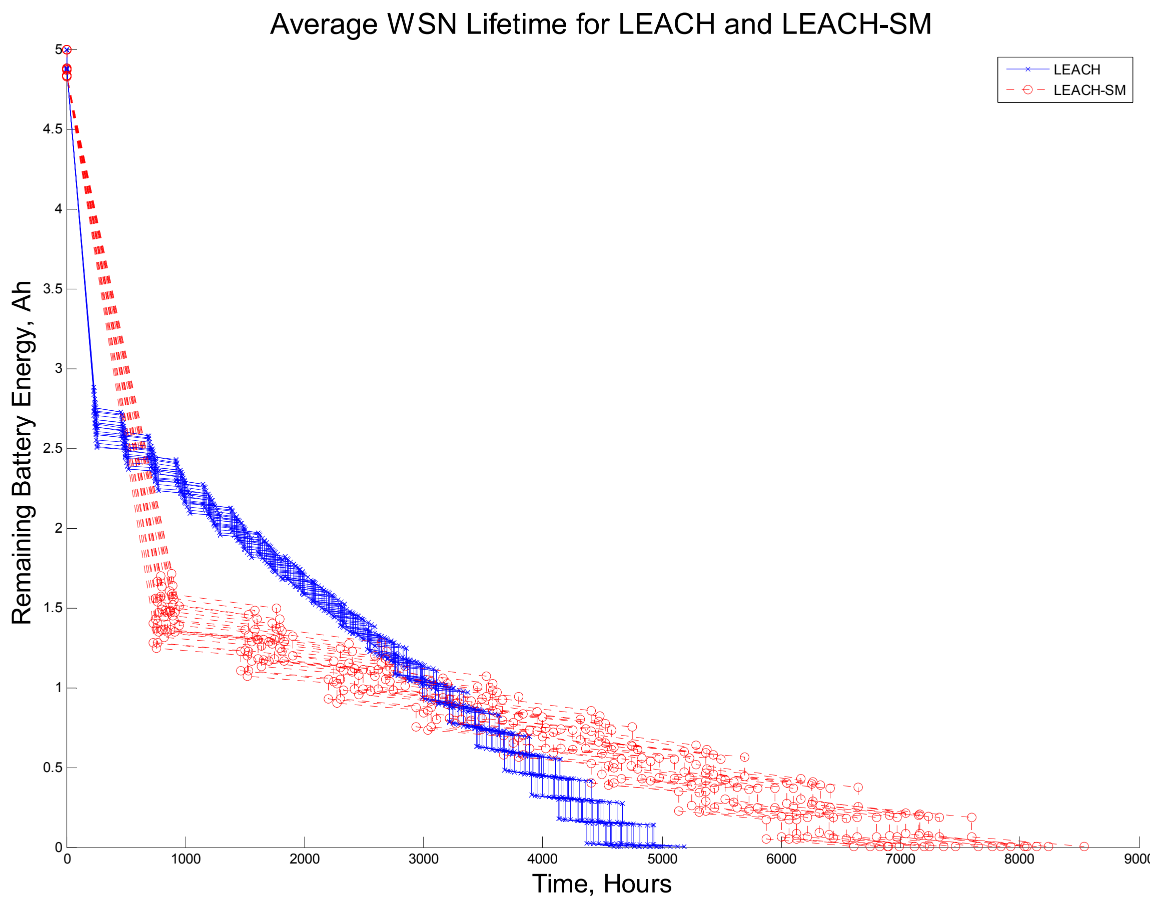


Figure 9.15. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH and for LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 50\%$ (based on 20 simulation runs).

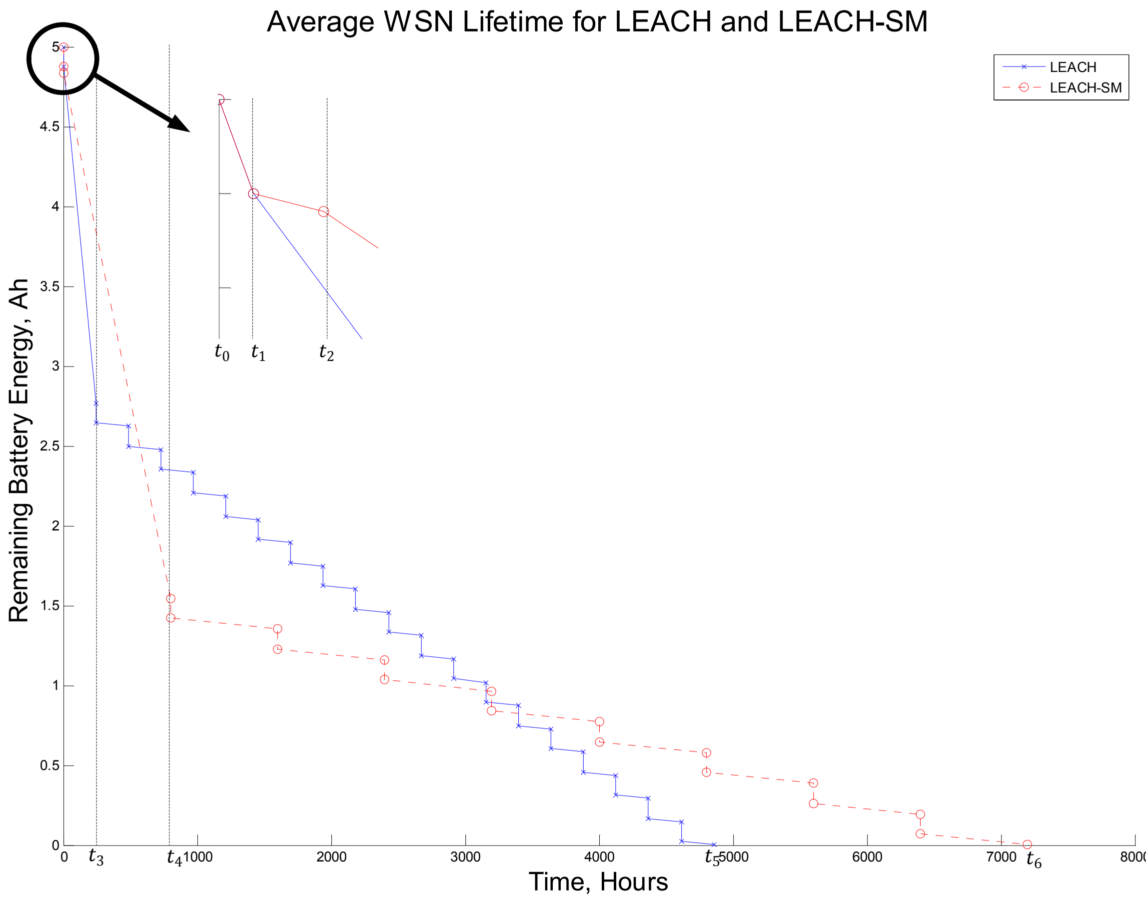


Figure 9.16. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 50\%$ (based on 20 simulation runs).

In both protocols, each node serves as a cluster head only once in its lifetime. This period of cluster head service corresponds to the steepest (initial) segment of each energy consumption curve.

The range of WSN lifetimes for LEACH is from 4756 h to 4956 h, and the range of WSN lifetimes in LEACH-SM is from 7100 h to 7300 h. This means that the *worst* case of WSN lifetime for LEACH-SM is 43% better than the *best* case of WSN lifetime for LEACH. However, the *best* case of WSN lifetime for LEACH-SM is 47% better than the *best* case of WSN lifetime for LEACH.

Figure 9.16 shows energy consumption curves and average WSN lifetime for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 50\%$. For LEACH, $[0, t_1]$ is the setup interval for a selected node in LEACH, $[t_1, t_3]$ is the interval when the node serves as a cluster head in LEACH, and $[t_3, t_5]$ is the interval when the node serves as a primary in LEACH. For LEACH-SM, $[t_0, t_1]$ is the setup interval for a selected node, $[t_1, t_2]$ is the spare selection phase, $[t_2, t_4]$ is the interval when the node serves as a cluster head, and $[t_3, t_5]$ is the interval when the node serves as a primary. (Line fragments parallel to the time axis indicate the nap periods—with no energy consumption.)

Figure 9.16 shows that a WSN in LEACH-SM can achieve lifetime longer than the same WSN in LEACH. For the simulated runs, WSN lifetime in LEACH-SM was longer about 48%.

9.5.1.2 Simulation Results for Ranges of σ^{CH} or α Values

We consider here six cases with different combinations of values for σ^{CH} (duration of a nap interval for a cluster head) and α (spare ratio)—as shown in Table 9.5.

Table 9.5. Comparison of LEACH-SM with LEACH.

Case Number	**Duration(s) of a nap interval for a cluster head (σ^{CH})**	**The spare ratio(s) for LEACH-SM (α)**	**Figures**	**Tables**
1.	0, 10, 20, 30	25%	Figure 9.17	Table A.1 Table A.2 Table A.5 Table A.6 Table A.9 Table A.10 Table A.13 Table A.14
2.	0, 10, 20, 30	50%	Figure 9.18	Table A.3 Table A.4 Table A.7 Table A.8 Table A.11 Table A.12 Table A.15 Table A.16

Table 9.5 – Continued

3.	0	25%, 50%	Figure 9.19	Table A.1 Table A.2 Table A.3 Table A.4
4.	10	25%, 50%	Figure 9.20	Table A.5 Table A.6 Table A.7 Table A.8
5.	20	25%, 50%	Figure 9.21	Table A.9 Table A.10 Table A.11 Table A.12
6.	30	25%, 50%	Figure 9.22	Table A.13 Table A.14 Table A.15 Table A.16

Case 1: $\sigma^{CH} = 0,10,20,30$ and $\alpha = 25\%$

Figure 9.17, shows eight individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 0, 10, 20, 30$ and $\alpha = 25\%$.

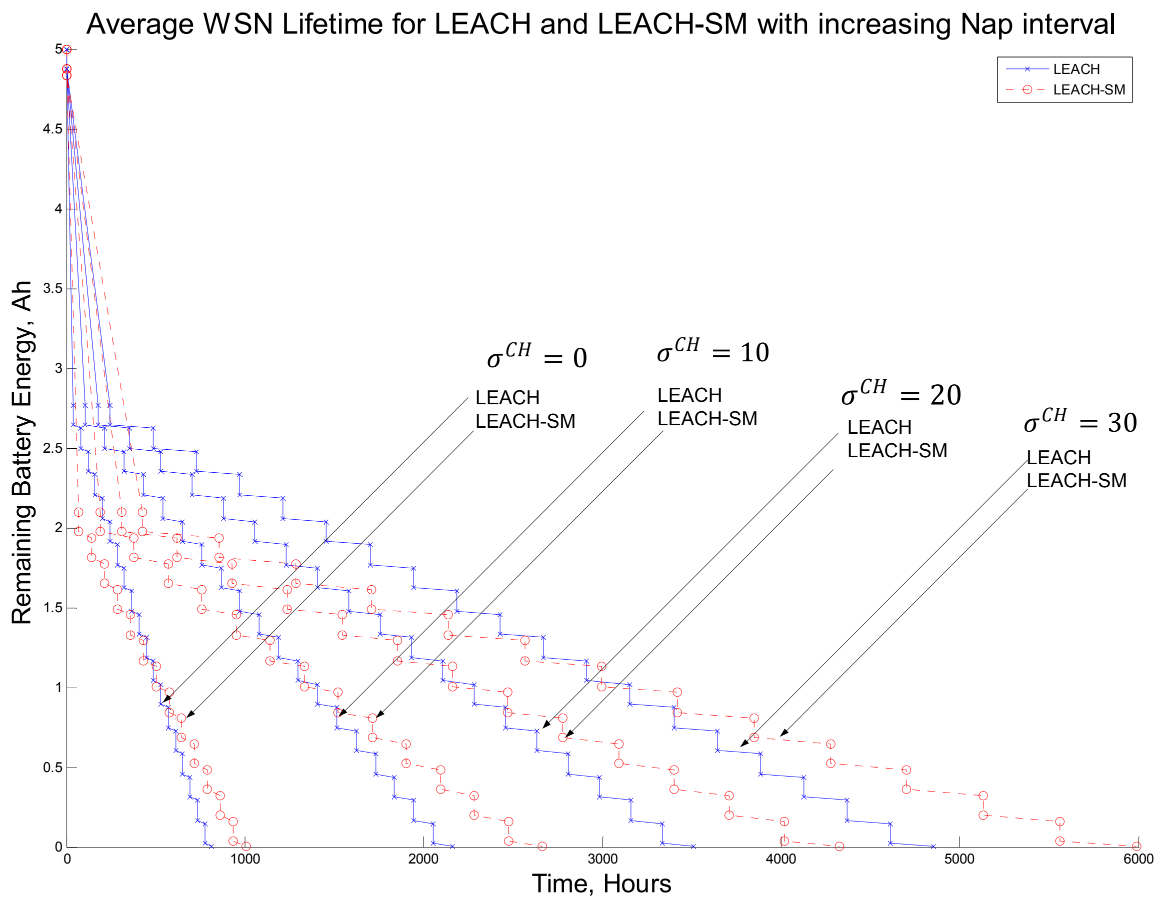


Figure 9.17. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM for parameter values: $\sigma^{CH} = 0, 10, 20, 30$ and $\alpha = 25\%$.

In both protocols, each node serves as a cluster head only once in its lifetime. This period of cluster head service corresponds to the steepest (initial) segment of each energy consumption curve.

WSN lifetime in LEACH-SM is 23% better than WSN lifetime in LEACH for all four combinations of values for σ^{CH} and α (cf. Figure 9.17).

Case 2: $\sigma^{CH} = 0, 10, 20, 30$ and $\alpha = 50\%$

Figure 9.18, shows eight individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 0, 10, 20, 30$ and $\alpha = 50\%$.

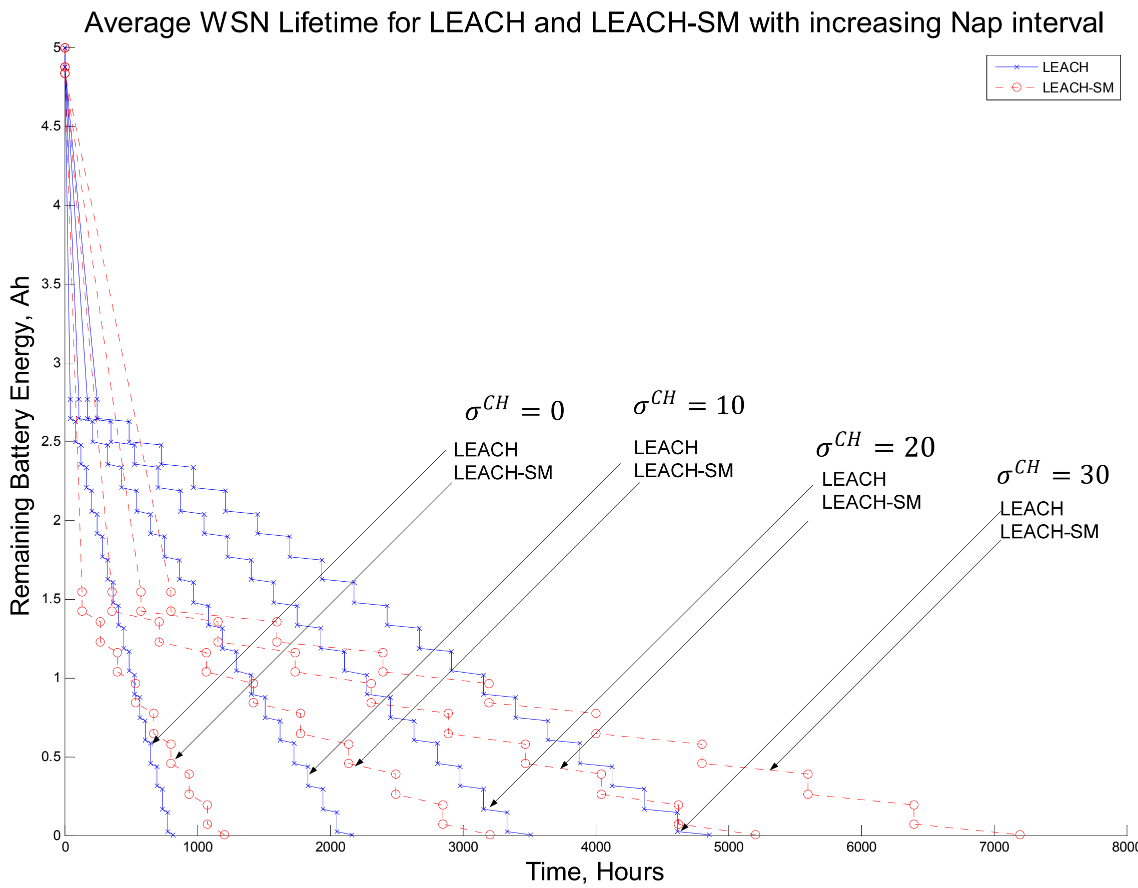


Figure 9.18. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM for parameter values: $\sigma^{CH} = 0, 10, 20, 30$ and $\alpha = 50\%$.

WSN lifetime for LEACH-SM is 48% better than the WSN lifetime for LEACH for all four combinations of values for σ^{CH} and α (cf. Figure 9.18).

Note that in Figure 9.17 and Figure 9.18, the comparison results give the lower bound on the WSN lifetime extension provided by LEACH-SM. The reason is that for LEACH-SM we consider the minimum number of primary nodes and no spares. The

Figure 9.17 summarizes only 4 of 8 cases, those with $\alpha = 25\%$ shown in Table 9.4. In this experiment we increase the Nap interval. At the beginning the value of the Nap interval is set to zero, that is, the duty cycle for cluster head in LEACH is 100%. In general, the duty cycle of cluster head in LEACH-SM is decreased by α %. We increased the Nap interval from 0 to 30 with step size of 10 each iteration until the duty cycle is 15%.

We observe that WSN lifetime for LEACH-SM is 23% better than the WSN lifetime for LEACH for all four combinations of values for σ^{CH} and α.

Figure 9.18 summarizes the remaining 4 cases, those with $\alpha = 50\%$, as shown in Table 9.4. As we did before in this experiment, at the beginning we set the value of the Nap interval to zero, that is, the duty cycle for LEACH is 100%. In this case α=50%. After that we increased the Nap interval at each iteration up to 30.

WSN lifetime in LEACH-SM is 48% and is better than WSN lifetime in LEACH, which is 23% for all four combinations of values for σ^{CH} and α.

Case 3: $\sigma^{CH} = 0$ and $\alpha = 25\%, 50\%$

Figure 9.19, shows only three individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 25\%\ and\ 50\%$.

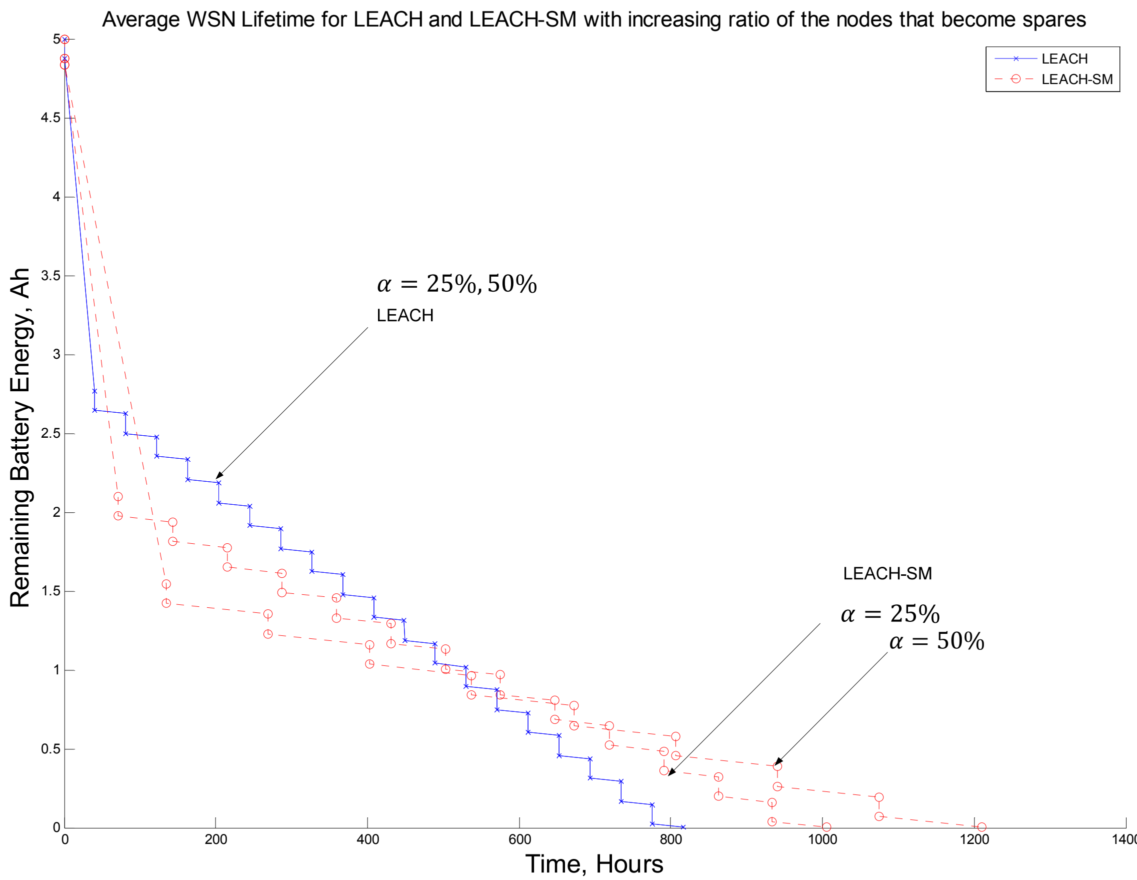


Figure 9.19. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM for parameter values: $\sigma^{CH} = 0$ and $\alpha = 25\%, 50\%$.

In Figure 9.19, we fixed Nap interval of cluster head and change the spare ratio (α) from 25% to 50%. As expected, there is no change in WSN lifetime for LEACH, because LEACH does not use spares. However, a significant increase in WSN lifetime is observed for LEACH-SM.

WSN lifetime for LEACH-SM is 23% better than the WSN lifetime for LEACH for $\sigma^{CH} = 0$ and $\alpha = 25\%$. We observe that WSN lifetime for LEACH-SM is 48% better than the WSN lifetime for LEACH when we set $\sigma^{CH} = 0$ and $\alpha = 50\%$.

The Figure 9.19 is in fact summarizes only 2 of 8 cases, those with $\sigma^{CH} = 0$ shown in Table 9.4. In this experiment we increase the spare ratio from 25% to 50% and fixed Nap interval for cluster head (σ^{CH}). Since $\sigma^{CH} = 0$, this means that the duty cycle for LEACH is 100% for both iterations. If α=25% of the sensor node are in passive mode (by using DESST), then the duty cycle of cluster head is decreased by α % in LEACH-SM. That is why WSN lifetime for LEACH-SM is 23% better than the WSN lifetime for LEACH.

In second iteration for α = 50%, we again set $\sigma^{CH} = 0$, which implies that the duty cycle of cluster head is 100% for LEACH. Therefore, the duty cycle of cluster head in LEACH-SM is decreased by α %. This results in extension of WSN lifetime by 48% compared to LEACH.

Case 4: $\sigma^{CH} = 10$ and $\alpha = 25\%, 50\%$

Figure 9.20, shows only three individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 25\%\ and\ 50\%$.

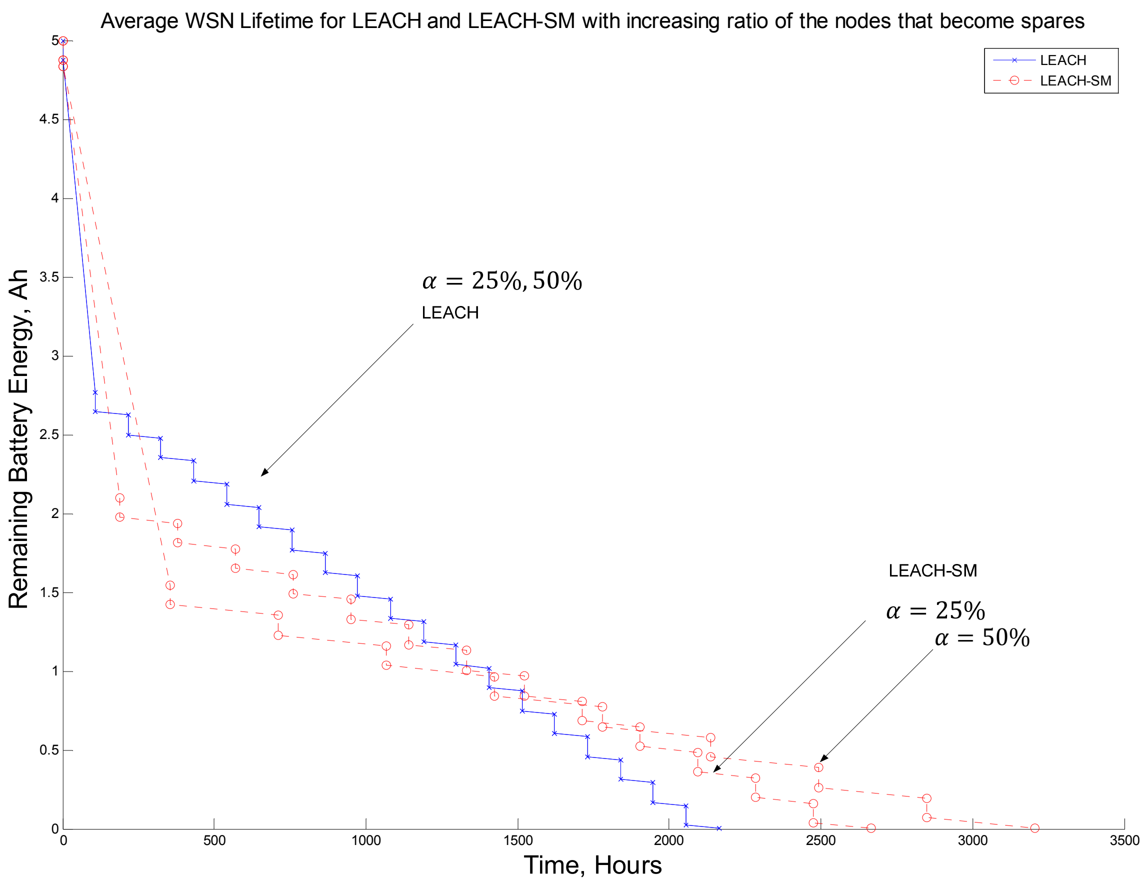


Figure 9.20. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM for parameter values: $\sigma^{CH} = 10$ and $\alpha = 25\%, 50\%$.

In Figure 9.20, we fixed Nap interval of cluster head and change the spare ratio (α) from 25% to 50%. As expected there is no change in WSN lifetime for LEACH, because LEACH does not use spares. However increase in WSN lifetime significantly observed in LEACH-SM.

WSN lifetime for LEACH-SM is 23% better than the WSN lifetime for LEACH for $\sigma^{CH} = 10$ and $\alpha = 25\%$. We observe that WSN lifetime for LEACH-SM is 48% better than the WSN lifetime for LEACH when we set $\sigma^{CH} = 10$ and $\alpha = 50\%$.

The Figure 9.20 is in fact summarizes only 2 of 8 cases, those with $\sigma^{CH} = 10$ shown in Table 9.4. In this experiment we increase the spare ratio from 25% to 50% and fixed Nap interval for cluster head (σ^{CH}). Since $\sigma^{CH} = 10$, this means that the duty cycle for LEACH is 37% for both iterations. If α=25% of the sensor node are in passive mode (by using DESST), then the duty cycle of cluster head in LEACH-SM is only 27%. That is why WSN lifetime for LEACH-SM is 23% better than the WSN lifetime for LEACH.

In second iteration for α=50%, we set $\sigma^{CH} = 0$, which implies that the duty cycle of cluster head is 37% for LEACH. The duty cycle of cluster head in LEACH-SM is 17%. This results in extension of WSN lifetime by 48% compared to LEACH.

Case 5: $\sigma^{CH} = 20$ and $\alpha = 25\%, 50$

Figure 9.21, shows only three individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 20$ and $\alpha = 25\%\ and\ 50\%$.

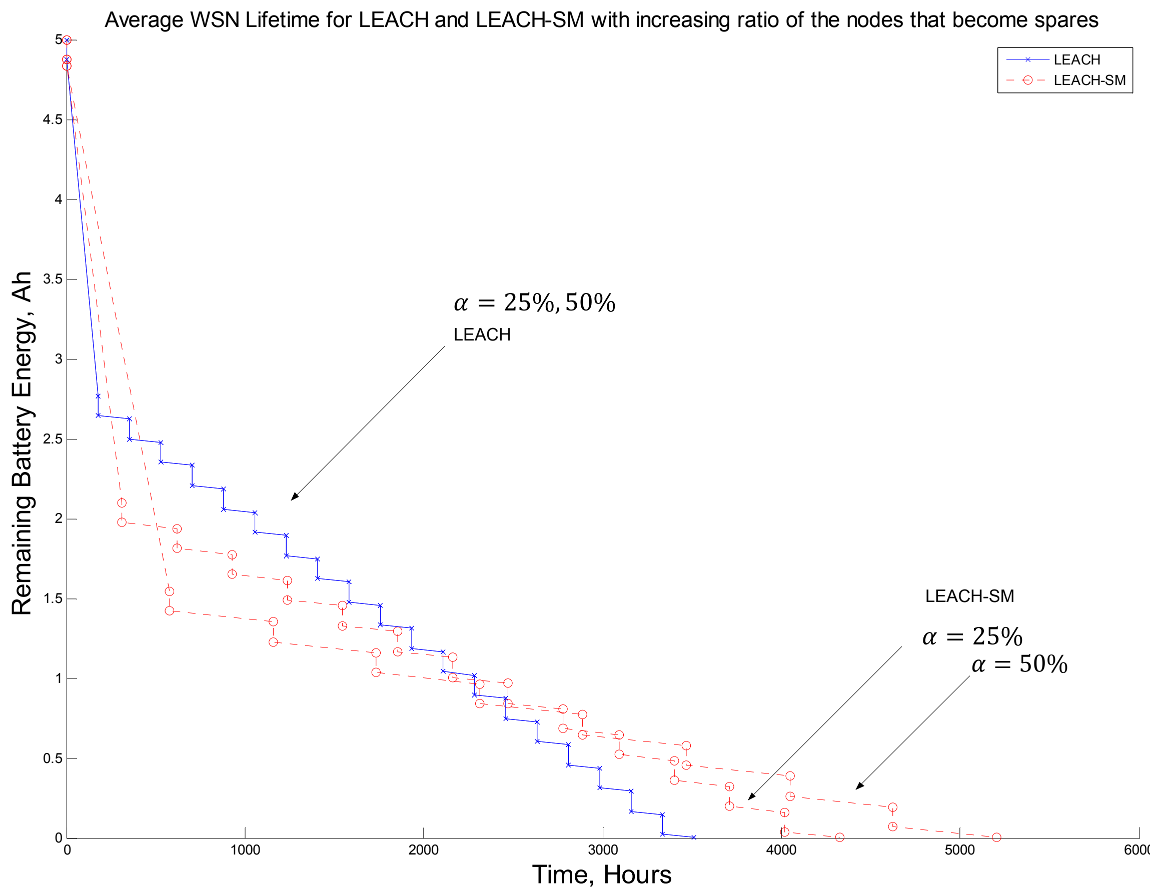


Figure 9.21. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM for parameter values: $\sigma^{CH} = 20$ and $\alpha = 25\%, 50\%$.

In Figure 9.21, we fixed Nap interval of cluster head and change the spare ratio (α) from 25% to 50%. As expected there is no change in WSN lifetime for LEACH, because LEACH does not use spares. However, significant increase in WSN lifetime is observed in LEACH-SM.

WSN lifetime for LEACH-SM is 23% better than WSN lifetime for LEACH for $\sigma^{CH} = 20$ and $\alpha = 25\%$. We observe that WSN lifetime for LEACH-SM is 48% better than WSN lifetime for LEACH when we set $\sigma^{CH} = 20$ and $\alpha = 50\%$.

The Figure 2.1 summarizes only 2 of 8 cases, namely those with $\sigma^{CH} = 20$ as shown in Table 9.4. In this experiment we increase the spare ratio from 25% to 50% and fix Nap interval for cluster head (σ^{CH}).

In the first case, α=25% and $\sigma^{CH} = 20$. The duty cycle of cluster head for LEACH is 23%. The duty cycle of cluster head for LEACH-SM is only 17%, which is significantly lower than 23% for LEACH. WSN lifetime for LEACH-SM is 23% (coincidentally also 23%) longer than WSN lifetime for LEACH.

In the second case, α=50% and $\sigma^{CH} = 20$. The duty cycle of cluster head for LEACH is again 23%. The duty cycle of cluster head in LEACH-SM is only 11%. WSN lifetime for LEACH-SM is 48% longer than WSN lifetime for LEACH.

Case 6: $\sigma^{CH} = 30$ and $\alpha = 25\%, 50$

Figure 9.22, shows only three individual energy consumption curves and WSN lifetimes for a single node for LEACH and LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 25\%$ *and* 50%..

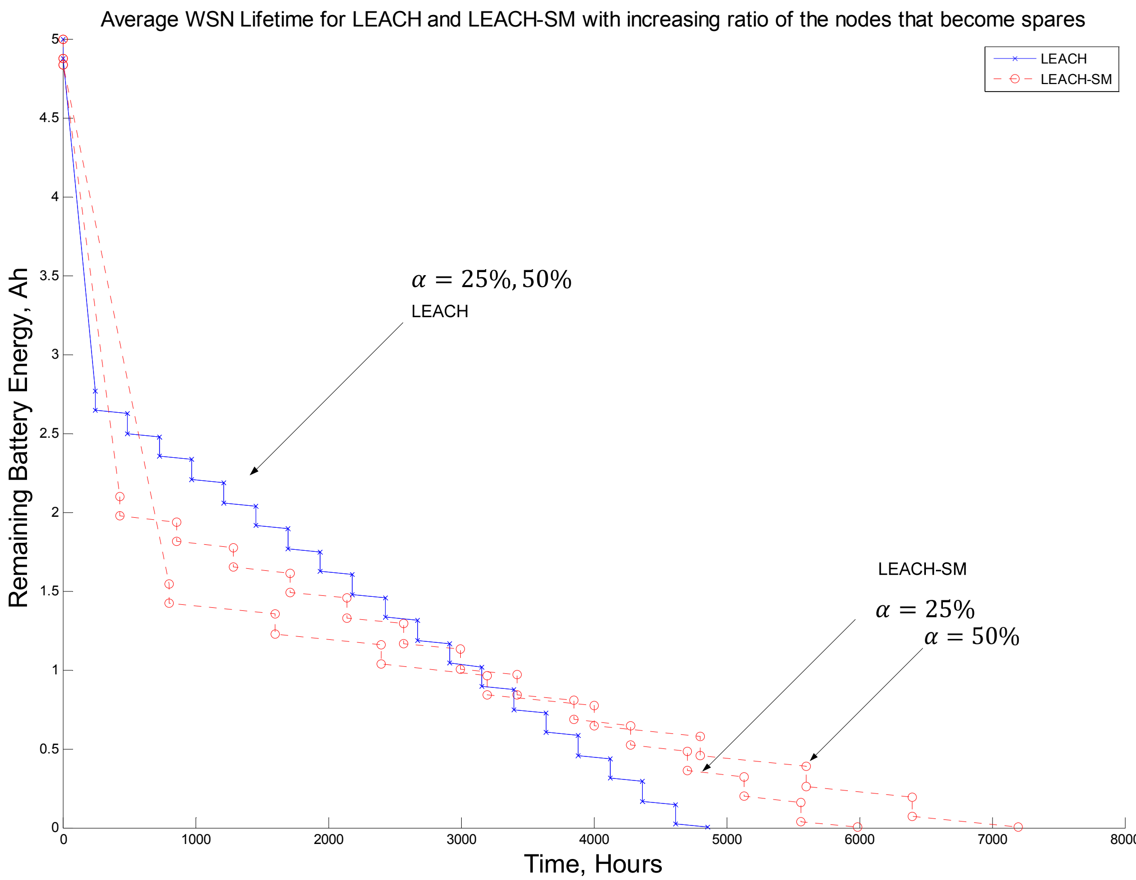


Figure 9.22. Average energy consumption curves and average WSN lifetimes for a single node for LEACH and LEACH-SM for parameter values: $\sigma^{CH} = 30$ and $\alpha = 25\%, 50\%$.

In Figure 9.22, we fixed Nap interval of cluster head and change the spare ratio (α) from 25% to 50%. As expected there is no change in WSN lifetime for LEACH, because LEACH does not use spares. However, significant increase in WSN lifetime is observed in LEACH-SM.

WSN lifetime for LEACH-SM is 23% better than WSN lifetime for LEACH for $\sigma^{CH} = 20$ and $\alpha = 25\%$. We observe that WSN lifetime for LEACH-SM is 48% better than WSN lifetime for LEACH when we set $\sigma^{CH} = 20$ and $\alpha = 50\%$.

The Figure 2.1 summarizes only 2 of 8 cases, namely those with $\sigma^{CH} = 30$ as shown in Table 9.4. In this experiment we increase the spare ratio from 25% to 50% and fix Nap interval for cluster head (σ^{CH}).

In the first case, α=25% and $\sigma^{CH} = 30$. The duty cycle of cluster head for LEACH is 17%. The duty cycle of cluster head for LEACH-SM is only 12%, which is significantly lower than 23% for LEACH. WSN lifetime for LEACH-SM is 23% (coincidentally also 23%) longer than WSN lifetime for LEACH.

In the second case, α=50% and $\sigma^{CH} = 30$. The duty cycle of cluster head for LEACH is again 23%. The duty cycle of cluster head in LEACH-SM is only 12%. WSN lifetime for LEACH-SM is 48% longer than WSN lifetime for LEACH.

9.5.2 Results of Energy Consumption and WSN Lifetime Simulations for LEACH-SM with Spare Replacements

This section presents the results of energy consumption and WSN lifetime simulation for LEACH-SM with spare replacement. The first subsection shows simulation results for individual combinations of values for σ^{CH} (duration of a nap interval for a cluster head) and α (spare ratio), while the second subsection shows simulation results for ranges of σ^{CH} or α values.

9.5.2.1 Simulation Results for Individual Combinations of σ^{CH} and α Values

Each replacement assures that WSN using LEACH-SM continues to live (without a next spare available, WSN would die if its coverage goes below the required minimum coverage). Note that each consecutive addition extends WSN lifetime by a smaller period (since a spare that waits for a longer time to become a primary uses more of its energy during its Awake-Nap cycles executed before becoming a primary).

There are no spares in LEACH. When a primary dies at time t_1 there is no replacement for it. Therefore, WSN can achieve longer lifetime if it uses LEACH-SM rather than LEACH.

For better understanding of the replacement process in LEACH-SM, let us consider the example.

Example: Replacement Process in LEACH-SM

Let us consider only two simple cases. We assume one cluster for the sake of simplicity. We also assume that the number of nodes remains fixed after each setup phase. Finally, we assume that there are 20 nodes in this cluster.

Case 1: $\alpha = 25\%$

To maintain the above-threshold target coverage let us assume that the spare ratio is 25%. Then, we have 5 spares and 15 primaries (including cluster head), as shown in Figure 9.23.

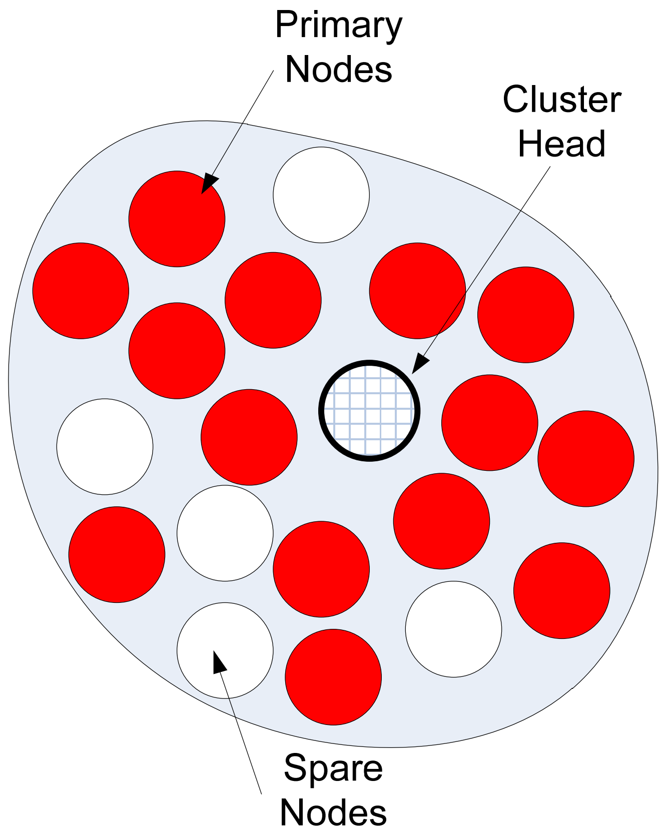


Figure 9.23. Illustration of a cluster with 20 nodes and $\alpha = 25\%$.

Recall that LEACH and LEACH-SM balance energy usage by a node in such a way that all initial primaries and cluster head die at nearly the same time. We simulate one node which starts as a cluster head. Other nodes behaves analogously (with the difference that they serve as a cluster head in different rounds).

In this case 15 nodes die nearly at the same time denoted as t_1. In Case 1 LEACH-SM attempts to replace all 15 primary nodes (including 1 cluster head and 14 regular nodes) as shown in Figure 9.23. However we have only 5 spares, so the replacement of 15 primary nodes is not possible. Therefore WSN dies at t_1.

Case 2: $\alpha = 50\%$

In this case, have 10 active nodes (incl. cluster head) and 10 spares as shown in Figure 9.24.

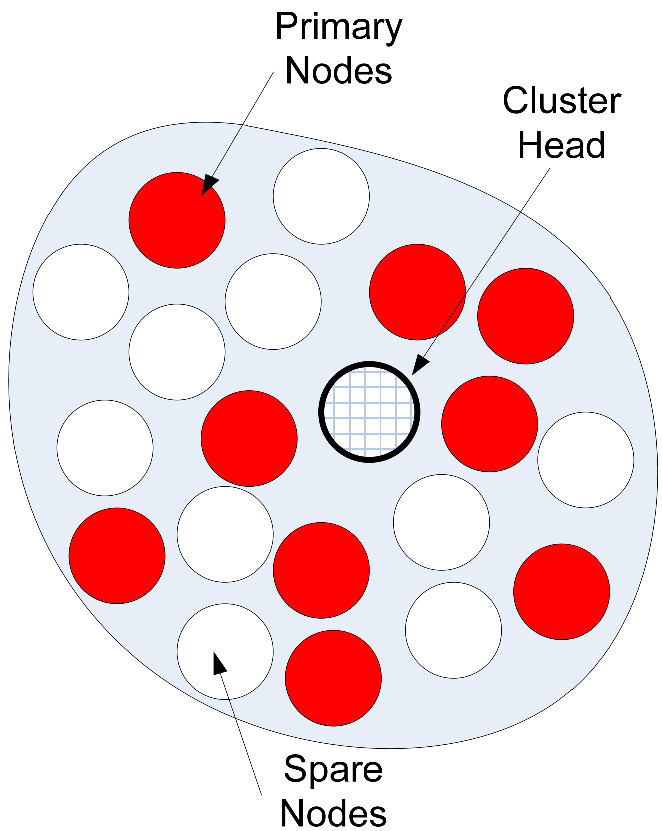


Figure 9.24. Illustration of a cluster with 20 nodes and $\alpha = 50\%$ at the deployment time.

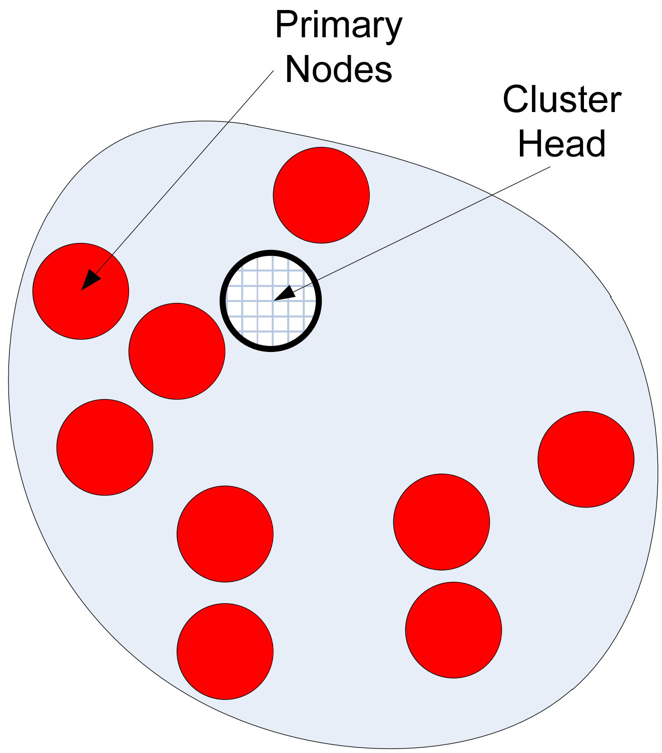


Figure 9.25. Illustration for a cluster with 20 nodes and $\alpha = 50\%$ after the first replacement at time t_1.

All primaries die simultaneously at time t_1. Figure 9.24 shows that we have 10 spare nodes available. Therefore in this case the first replacement is possible. After the first replacement, we have 10 primaries (including cluster head) and 0 spares as shown in Figure 9.25.

At time t_2, all primaries die simultaneously. We have no spares to replace them, so WSN dies as well.

Figure 9.25 shows that we have 0 spares available at time t_2. Therefore, in this case the second replacement is not possible.

Table 9.6. Cases to measure WSN lifetime when replacements of exhausted primary nodes by spares are allowed.

Sr.	**Duration of a nap interval of a cluster head (σ^{CH})**	**The spare ratio(s) for LEACH-SM (α)**	**Figures**	**Tables**
1.	0	50%	Figure 9.26, Figure 9.27	Table A.4
2.	10	50%	Figure 9.28, Figure 9.29	Table A.8
3.	20	50%	Figure 9.30, Figure 9.31	Table A.12
4.	30	50%	Figure 9.32, Figure 9.33	Table A.16

It is clear from the above example that the replacement process is possible only if the spare ratio is 50% or more provided all spares are able to cover the targets covered by primaries that exhausted their energy.

We consider here 4 cases with different combinations of values for σ^{CH} (duration of a nap interval for a cluster head) and $\alpha = 50\%$ (spare ratio)—as shown in Table 9.6. Since we consider WSN lifetimes when spare replacements of exhausted primaries are allowed, there are no results for LEACH (because LEACH uses no spares).

Each former spare that became a primary is in turn replaced by another spare when its energy is exhausted. Each replacement assures that WSN continues to live (without a next spare available, WSN would die if its target coverage goes below the required minimum coverage).

Case 1: $\sigma^{CH} = 0$ and $\alpha = 50\%$

Figure 9.26 and Figure 9.27 shows energy consumption curves for an exhausted primary, and a spare s_1 that replaced it. More precisely, the first of these figures shows results of 20 simulation runs; it shows twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 50\%$. Table A.18 in Appendix A gives the detailed numerical results for these 20 runs.

Figure 9.27 shows the average WSN lifetimes and the energy consumption curves for an exhausted primary, and a spare s_1 that replaced it. At time t_1, the primary dies, and is replaced by spare s_1, which already used up $5 - e_1$ of its energy (as shown by the blue curve). After time t_1, s_1 is a primary and consumes more energy, as shown by the steeper red curve.

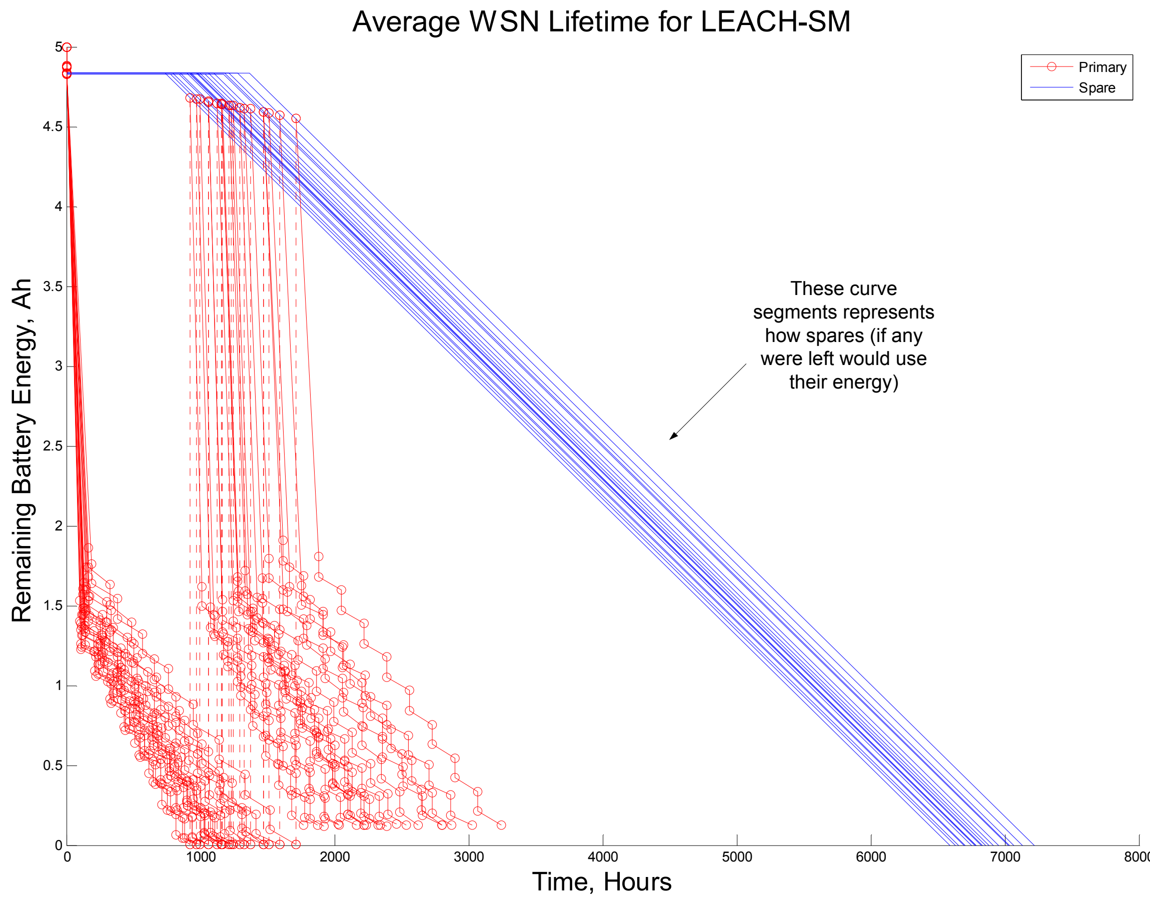


Figure 9.26. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 50\%$ (based on 20 simulation runs).

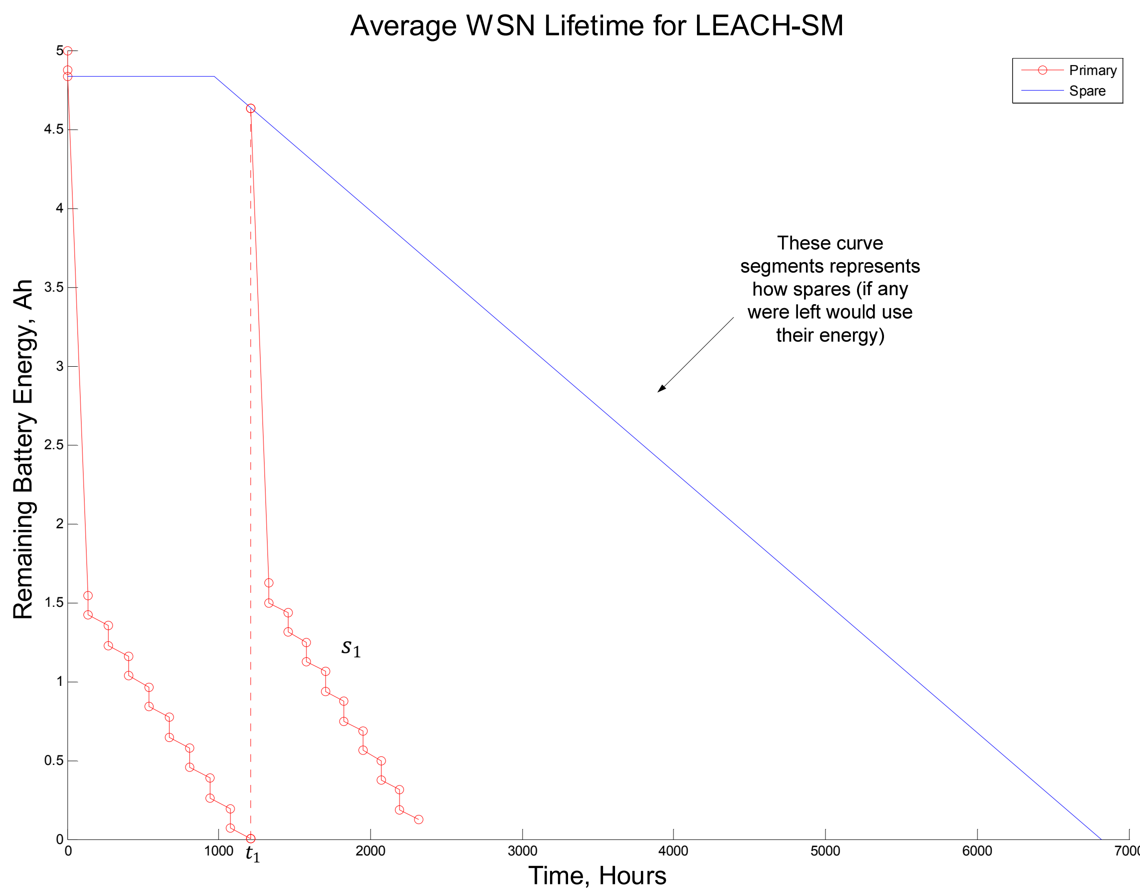


Figure 9.27. Average WSN lifetime for LEACH-SM with $\sigma^{CH} = 0$ and $\alpha = 50\%$. The energy consumption curves for an exhausted primary, and a spare s_1 that replaced it.

Case 2: $\sigma^{CH} = 10$ and $\alpha = 50\%$

Figure 9.28 and Figure 9.29 shows energy consumption curves for an exhausted primary, and a spare s_1 that replaced it. More precisely, the first of these figures shows results of 20 simulation runs; it shows twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 50\%$. Table A.20 in Appendix A gives the detailed numerical results for these 20 runs.

Figure 9.29 shows the average WSN lifetimes and the energy consumption curves for an exhausted primary, and a spare s_1 that replaced it. At time t_1, the primary dies, and is replaced by spare s_1, which already used up $5 - e_1$ of its energy (as shown by the blue curve). After time t_1, s_1 is a primary and consumes more energy, as shown by the steeper red curve.

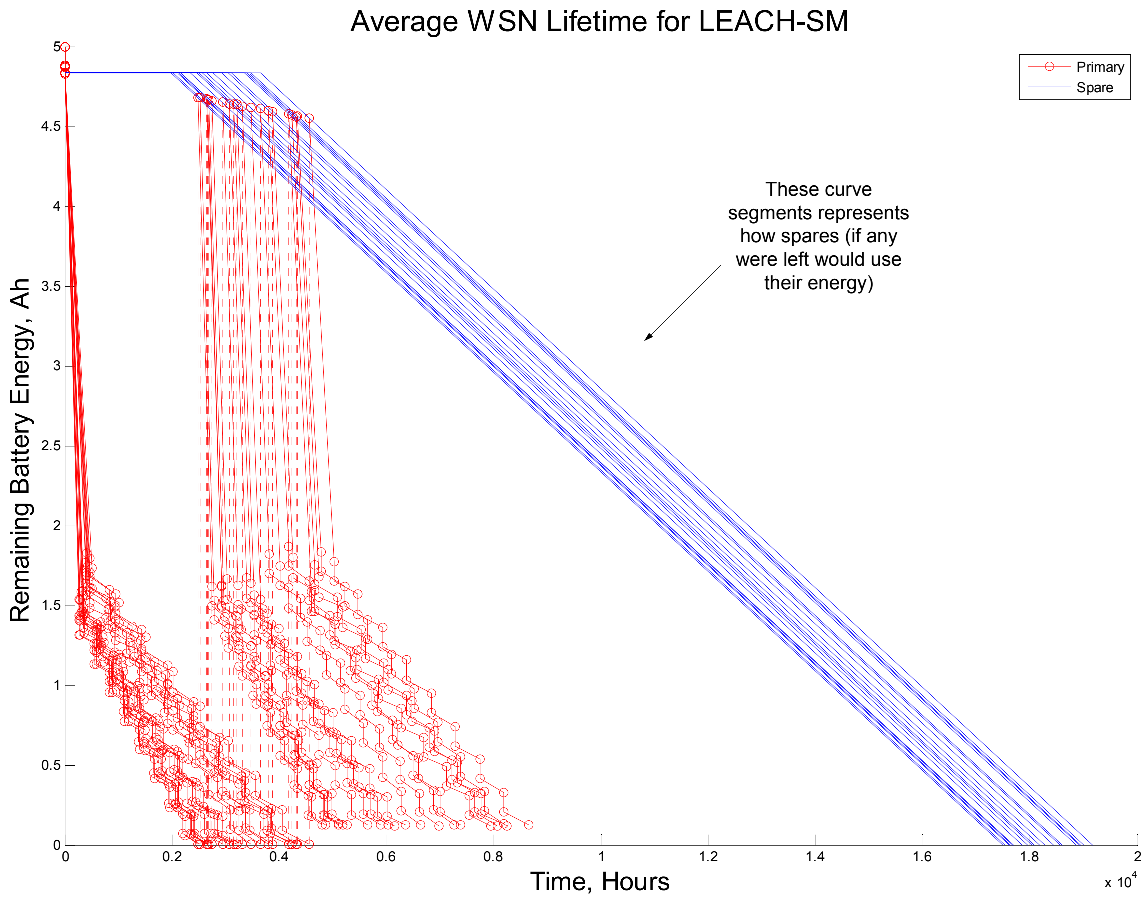


Figure 9.28. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 50\%$ (based on 20 simulation runs).

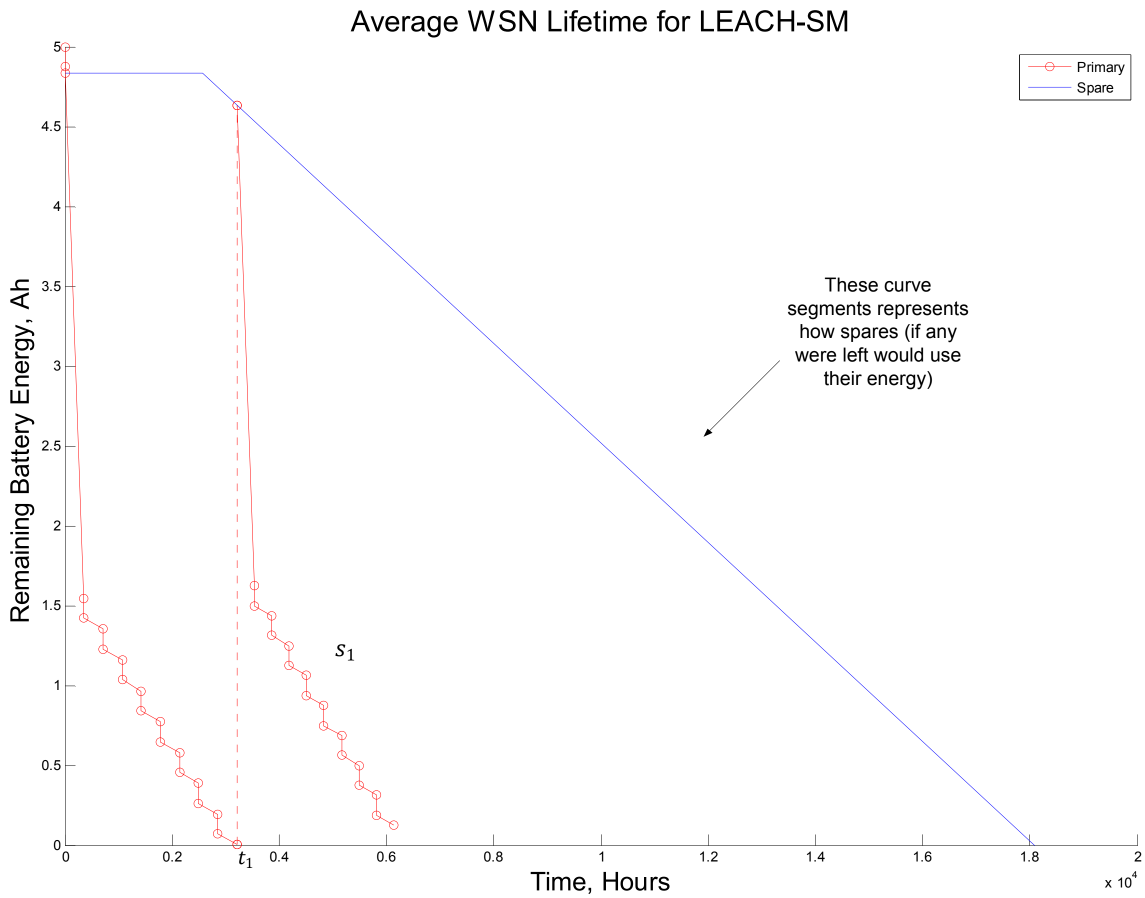


Figure 9.29. Average WSN lifetime for LEACH-SM with $\sigma^{CH} = 10$ and $\alpha = 50\%$.

Case 3: $\sigma^{CH} = 20$ and $\alpha = 50\%$

Figure 9.30 and Figure 9.31 shows energy consumption curves for an exhausted primary, and a spare s_1 that replaced it. More precisely, the first of these figures shows results of 20 simulation runs; it shows twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH-SM with $\sigma^{CH} = 20$ and

$\alpha = 50\%$. Table A.22 in Appendix A gives the detailed numerical results for these 20 runs.

Figure 9.31 shows the average WSN lifetimes and the energy consumption curves for an exhausted primary, and a spare s_1 that replaced it. At time t_1, the primary dies, and is replaced by spare s_1, which already used up $5 - e_1$ of its energy (as shown by the blue curve). After time t_1, s_1 is a primary and consumes more energy, as shown by the steeper red curve.

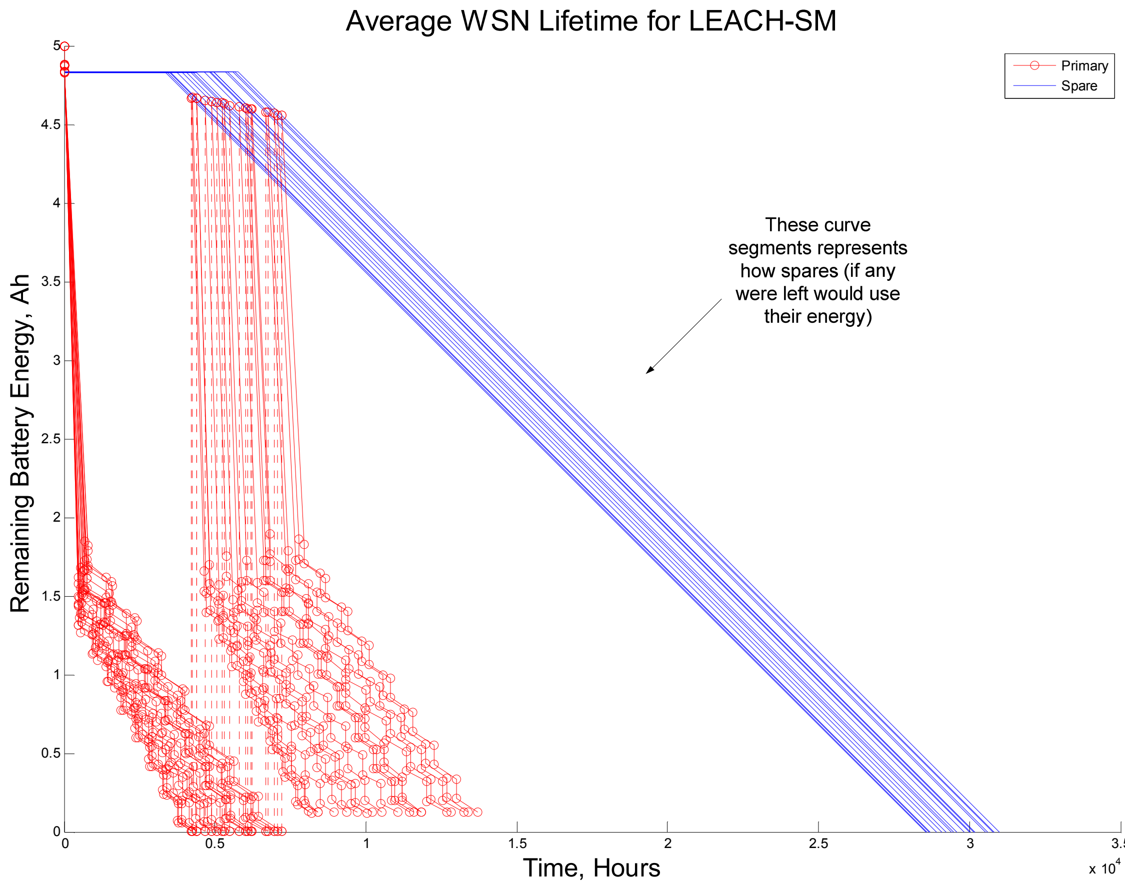


Figure 9.30. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH-SM with $\sigma^{CH} = 20$ and $\alpha = 50\%$ (based on 20 simulation runs).

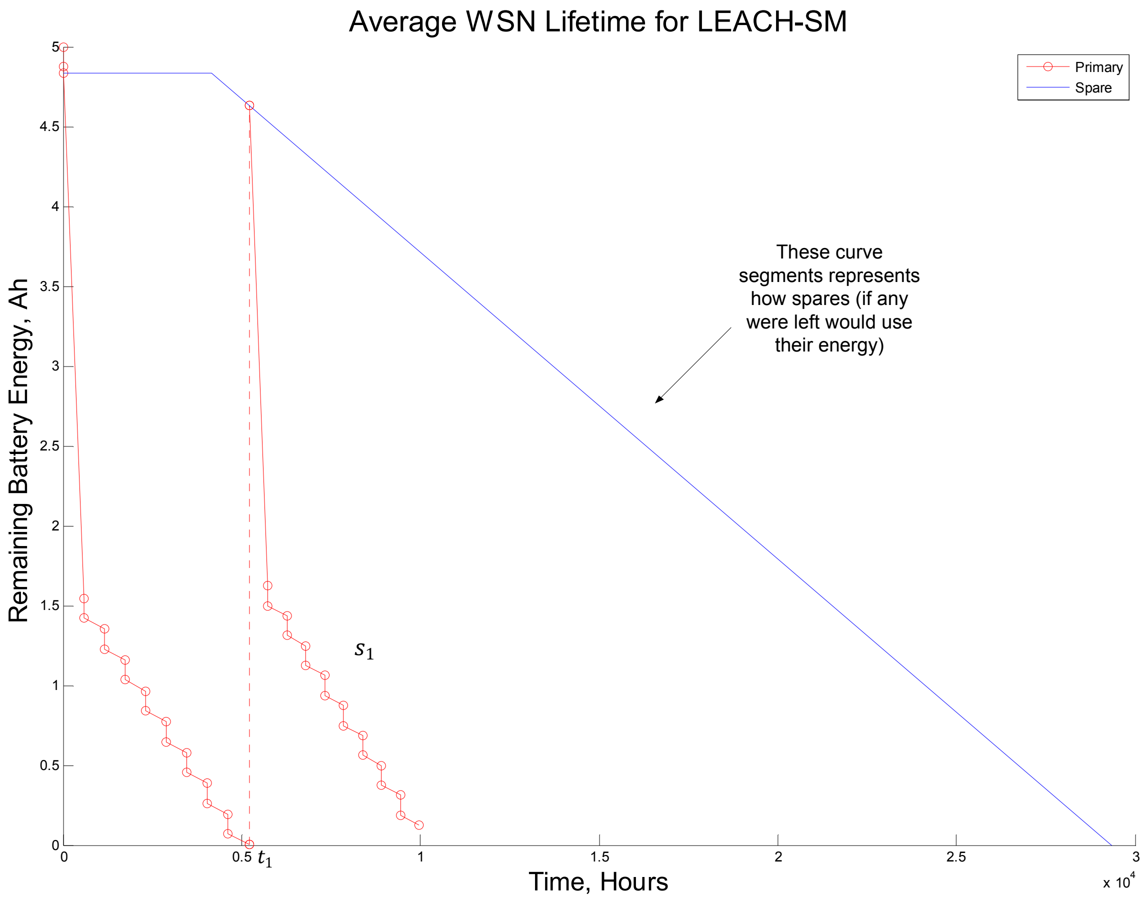


Figure 9.31. Average WSN lifetime for LEACH-SM with $\sigma^{CH} = 20$ and $\alpha = 50\%$.

Case 4: $\sigma^{CH} = 30$ and $\alpha = 50\%$

Figure 9.32 and Figure 9.33 shows energy consumption curves for an exhausted primary, and a spare s_1 that replaced it. More precisely, the first of these figures shows results of 20 simulation runs; it shows twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 50\%$. Table A.24 in Appendix A gives the detailed numerical results for these 20 runs.

Figure 9.33 shows the average WSN lifetimes and the energy consumption curves for an exhausted primary, and a spare s_1 that replaced it. At time t_1, the primary dies, and is replaced by spare s_1, which already used up $5 - e_1$ of its energy (as shown by the blue curve). After time t_1, s_1 is a primary and consumes more energy, as shown by the steeper red curve.

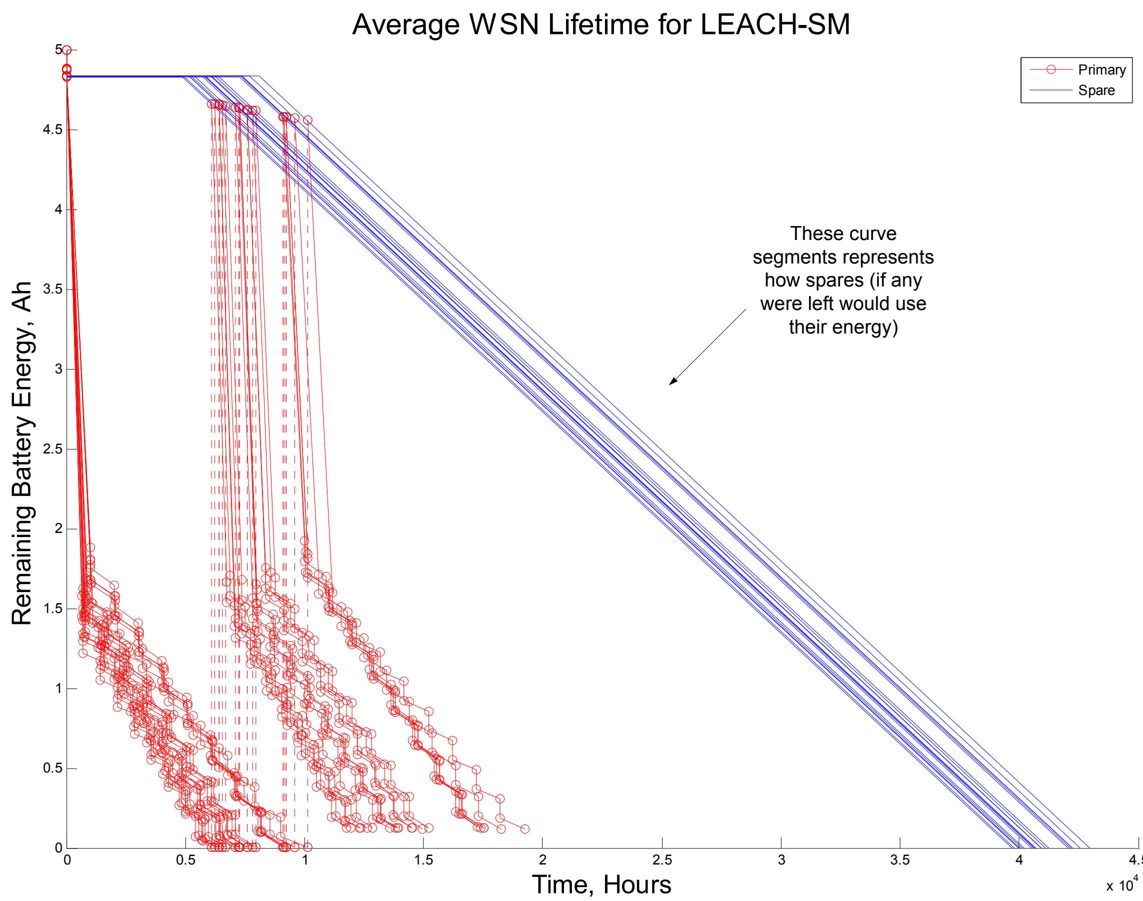


Figure 9.32. Twenty individual energy consumption curves and twenty individual WSN lifetimes for a single node for LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 50\%$ (based on 20 simulation runs).

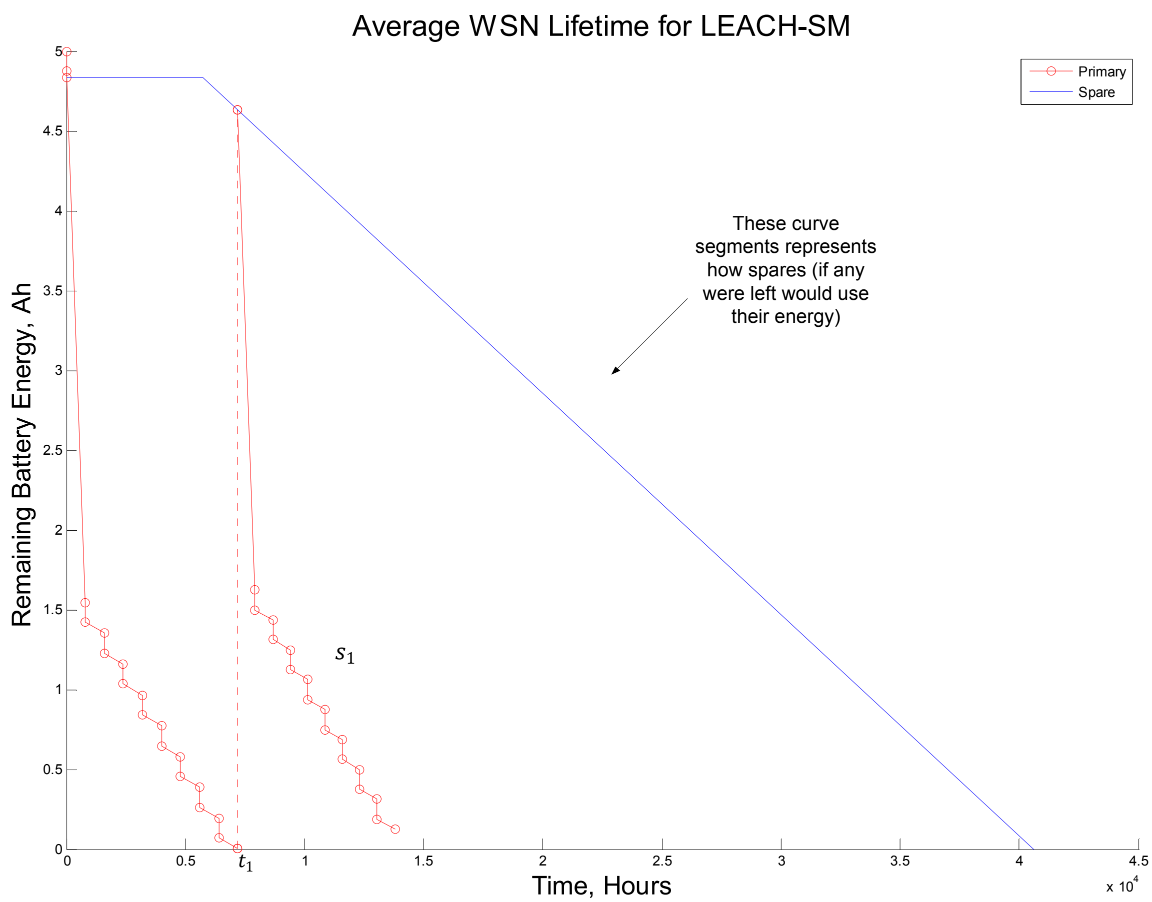


Figure 9.33. Average WSN lifetime for LEACH-SM with $\sigma^{CH} = 30$ and $\alpha = 50\%$.

9.5.2.2 Simulation Results for Ranges of σ^{CH} or α Values

We consider here only one case with different combinations of values for σ^{CH} (duration of a nap interval for a cluster head) and α (spare ratio)—as shown in Table 9.7.

Table 9.7. LEACH-SM with one replacement.

Case Number	**Duration(s) of a nap interval for a cluster head (σ^{CH})**	**The spare ratio(s) for LEACH-SM (α)**	**Figures**	**Tables**
1.	0, 10, 20, 30	50%	Figure 9.34	Table A.18 Table A.20 Table A.22 Table A.24 Table A.16

Case 1: $\sigma^{CH} = 0, 10, 20, 30$ and $\alpha = 50\%$

Figure 9.34, shows eight individual energy consumption curves and average WSN lifetimes for a single node for LEACH-SM with $\sigma^{CH} = 0, 10, 20, 30$ and $\alpha = 50\%$.

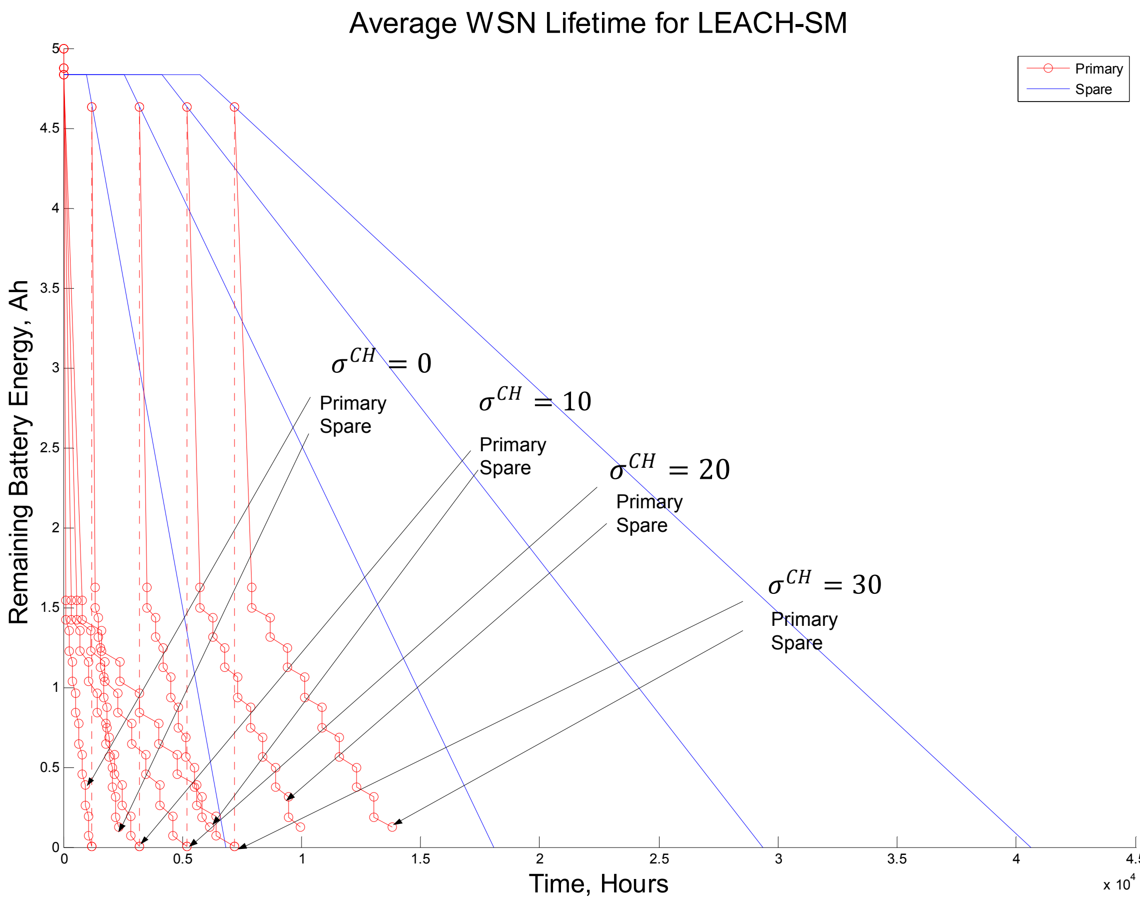


Figure 9.34. Average energy consumption curves and average WSN lifetimes for a single node for LEACH-SM for parameter values: $\sigma^{CH} = 0, 10, 20, 30$ and $\alpha = 50\%$.

WSN lifetime in LEACH-SM is 183% longer than WSN lifetime in LEACH for all four combinations of values for σ^{CH} and α thanks to just one replacement (cf. Figure 9.34).

The Figure 9.34 summarizes only 4 of 8 cases, namely those with $\alpha = 25\%$, as shown in Table 9.8.

Table 9.8. Average WSN lifetime for a single node for LEACH and LEACH-SM.

Duration of a nap interval for a cluster head (σ^{CH})	The spare ratio(s) for LEACH-SM (α)	WSN Lifetime		Average Increase in WSN Lifetime
		LEACH	LEACH-SM	
0	25%	816 [h]	1006 [h]	23%
0	50%	816 [h]	1210 [h]	48%
10	25%	2162 [h]	2669 [h]	23%
10	50%	2162 [h]	3206 [h]	48%
20	25%	3510 [h]	4327 [h]	23%
20	50%	3510 [h]	5228 [h]	48%
30	25%	4856 [h]	5988 [h]	23%
30	50%	4856 [h]	7200 [h]	48%

9.6 Simulation Conclusions

Simulation experiments were used for evaluation and comparison of the LEACH and LEACH-SM protocols. Two of the eight random variables were used as control variables (the spare ratio and duration of the nap interval for cluster heads). Recall that these two variables were selected because they express the main differences between LEACH and LEACH-SM.

Each simulation run tested a range of values for all eight random variables, i.e., the spare ratio for LEACH-SM, duration of a Nap interval of a cluster head, duration of the Awake interval of a cluster head in LEACH, duration of the Awake interval of a cluster head in LEACH-SM, duration of the setup interval in LEACH, duration of the setup interval in LEACH-SM, duration of the Awake interval of a regular node in LEACH, and duration of the Awake interval of a regular node in LEACH-SM.

The results of evaluating performance of and comparing LEACH and LEACH-SM in terms of their energy consumption and WSN lifetime were shown in tables (Table A.1 to Table A.24) and figures (Figure 9.1 to Figure 9.34).

Even when no spares are used, LEACH-SM achieves 23% to 48% extension of the average WSN lifetime when compared to LEACH (this is due to switching off redundant nodes in LEACH-SM). This advantage of using LEACH-SM is constant for the range of values for the duration of a nap interval for a cluster head (σ^{CH}). The advantage of using LEACH-SM grows with the spare ratio (α).

When LEACH-SM uses spares, LEACH-SM achieves 183% extension of the average WSN lifetime when compared to LEACH (which is unable to use spares).

10. CONCLUSIONS

10.1 Summary

Extending the period of operation (*lifetime*) of *wireless sensor networks (WSNs)* is one of the most critical issues for WSN applications. Lifetime limitations are caused by typically limited energy resources available to sensor nodes from their batteries.

The research results reported in the literature reveal that significant extensions of WSN lifetime can be achieved by adding *spare nodes*. *Spares* are ready to switch on when any original (*primary*) WSN node exhausts its energy. Spares have to be properly managed. Otherwise, they might hurt WSN lifetime rather than help it. For example, if more spares than needed are activated (become primaries), then WSN can have unnecessarily redundant coverage of some targets (while typically a WSN should provide only the minimum required target coverage with minimal possible redundancy). Sensor nodes that cover targets covered by other nodes waste their energy. In addition, redundant target coverage results in transmission of redundant data to cluster heads (which collect sensed data from sensor nodes), forcing them to waste energy for processing redundant data. Both energy wastes results in shortening WSN lifetime.

To achieve WSN lifetime extension, we propose the LEACH-SM protocol, which modifies the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol by providing an optimal spare selection and energy-saving management of spares. LEACH-SM adds the spare selection phase to LEACH.

Key feature of LEACH-SM are: extending WSN lifetime, maintaining the above-threshold target coverage throughout the WSN lifetime, reducing transmission of redundant data to cluster heads, allowing sensor nodes in all clusters to decide in parallel if they want be primaries (cluster heads or regular nodes) or spares, making spare selection at the beginning of its operation before WSN deployment, and assuring scalability by using only local information in the proposed optimization algorithms.

The research also presents a quantitative comparison of energy consumption by WSN nodes and WSN lifetimes in both protocols. We first provided an analytical quantitative comparison for special cases (defined by simplifying assumptions, providing "convenient" combinations of variable values that enable analytical approach). This was done by obtaining closed formulas for energy consumption for these special cases. The closed formulas we obtained calculate, among others: (i) the number of frames per round in LEACH and LEACH-SM; (ii) WSN lifetime for LEACH and LEACH-SM; (iii) WSN lifetime for two main variants of LEACH: LEACH-C and LEACH-F; (iv) residual WSN lifetime for LEACH and LEACH-SM; and (v) residual WSN lifetime for LEACH-C and LEACH-F.

Then, we run simulation experiments for complex cases, including using random variable values for two critical parameters. With the help of simulations run in MATLAB, we observe that WSN lifetime is longer when LEACH-SM is used than when LEACH is used.

10.2 Contributions

The LEACH-SM protocol enhances LEACH with an efficient management of spares; both are defined for WSNs with static sensor nodes and static targets. LEACH-SM deals with energy-consumption inefficiencies of LEACH.

The LEACH-SM protocol achieves the following objectives:

- Extending WSN lifetime (which is equivalent to extending the period for which WSN maintains the above-threshold coverage).
- Reducing transmission of redundant data to cluster heads.
- Allowing all sensor nodes in all clusters to decide in parallel if they become primaries or spares (done via Decentralized Energy-efficient Spare Selection Technique or DESST).
- Maintaining scalability by using only local information for optimization algorithms.

In addition, this Thesis provided evaluation and comparisons of LEACH and LEACH-SM using analytical techniques (for simplified cases) and simulation techniques (for general cases). We studied the impact of the spare ratio and duration of the nap interval of cluster heads on the WSN lifetime for LEACH and LEACH-SM.

Even when no spares are used, LEACH-SM achieves 23% to 48% extension of the average WSN lifetime when compared to LEACH. When LEACH-SM uses spares, LEACH-SM dominates LEACH by providing even 183% longer WSN lifetime.

10.3 Future Work

The following topics are beyond the scope of this dissertation, and might be important extensions of work described above.

First, LEACH-SM is designed for static sensor nodes and static targets. In the future, plan to extend it for mobile targets and for managing mobile node.

Second, more work on a detailed analytical comparison of WSN management protocols is needed. In the current performance analysis for LEACH-SM we use only the minimum number of primaries required for above-threshold coverage threshold.

We assume above that the number of clusters is fixed in each round, and the number of nodes in each cluster is fixed as well. We plan to relax these assumptions, and study the impact on the WSN lifetime for LEACH and LEACH-SM of the following factors: the spare ratio, the number of clusters in each round, the number of nodes in each cluster, and duration of the nap interval of cluster heads. These analyses will generalize the current analysis.

Third, in the future, security vulnerabilities of LEACH-SM must be considered. Protecting sensitive data gathered by sensors is one area of significant importance for WSNs. Security of routing is another critical challenge. Many attacks on WSN routing protocols are possible. The traditional end-to-end security mechanisms do not help, because they are more power hungry, need extra processing speed and communication requirements. The limited energy resources of sensor nodes are the main hurdle.

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APPENDIX A

Table A.1 WSN lifetime for LEACH.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	0
The ratio of the cluster nodes that become spares	25%

LEACH				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1646	41.7779	793.7799	835.7223
2	0.1684	40.2420	764.5976	805.0079
3	0.1637	40.5724	770.8760	811.6121
4	0.1722	41.6117	790.6231	832.4071
5	0.1612	41.6800	791.9209	743.7621
6	0.1656	42.5828	809.0725	855.8209
7	0.1631	43.1809	820.4368	810.7808
8	0.1676	40.9601	778.2417	845.3694
9	0.1650	41.7262	792.7978	844.6890
10	0.1625	43.6738	829.8018	773.6381
11	0.1711	38.6747	734.8190	773.6648
12	0.1711	40.7533	774.3133	815.2378
13	0.1638	42.4535	806.6173	849.2346
14	0.1717	39.8340	756.8460	796.8518
15	0.1702	42.3668	804.9688	847.5058
16	0.1692	40.1829	763.4752	803.8273
17	0.1694	41.8887	795.8844	837.9424
18	0.1681	39.9909	759.8274	799.9864
19	0.1665	41.6487	791.3246	833.1398
20	0.1668	40.1644	763.1244	803.4557
Sum	3.34	825.97	15693.35	16319.66
Mean	0.17	41.30	784.67	815.98
SD	0.00	1.25	23.78	29.65

Table A.2. WSN lifetime for LEACH-SM SM without spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	0
The ratio of the cluster nodes that become spares	25%

LEACH-SM				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1630	62.2949	1183.6000	946.1000
2	0.1694	65.8005	1250.2000	1070.9000
3	0.1628	54.8442	1042.0000	1097.0000
4	0.1660	50.9177	967.4357	918.5000
5	0.1702	61.5767	1170.0000	935.7000
6	0.1700	48.6766	924.8548	978.7013
7	0.1627	53.3434	1013.5000	1067.0000
8	0.1627	53.1883	1010.6000	1063.9000
9	0.1656	66.7438	1268.1000	1035.0000
10	0.1638	69.4594	1319.7000	918.5000
11	0.1666	60.1534	1142.9000	1203.2000
12	0.1623	58.2483	1106.7000	1165.1000
13	0.1622	52.2893	993.4963	1045.9000
14	0.1618	63.7385	1211.0000	974.9000
15	0.1616	57.6631	1095.6000	953.4000
16	0.1661	60.7959	1155.1000	1216.1000
17	0.1687	61.1798	1162.4000	1123.8000
18	0.1620	50.4174	957.9304	1008.5000
19	0.1661	58.0083	1102.2000	960.3000
20	0.1699	56.8342	1079.9000	936.9000
Sum	3.30	1166.17	22157.22	20619.40
Mean	0.17	58.31	1107.86	1030.97
SD	0.00	5.79	110.00	93.74

Table A.3. WSN lifetime for LEACH.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	0
The ratio of the cluster nodes that become spares	50%

LEACH				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1703	38.2803	727.3264	765.7770
2	0.1624	40.9372	777.8070	818.9066
3	0.1666	39.4225	749.0266	788.5157
4	0.1626	40.9211	777.5005	818.4842
5	0.1653	41.6954	792.2126	834.0733
6	0.1660	40.8646	776.4278	817.4584
7	0.1613	42.5052	807.5989	850.2655
8	0.1661	42.8020	813.2385	856.2067
9	0.1649	40.9695	778.4200	819.5544
10	0.1622	40.9695	778.4200	819.5517
11	0.1652	40.1532	762.9111	803.2295
12	0.1626	40.7807	774.8340	815.7773
13	0.1658	42.9440	815.9357	859.0455
14	0.1678	40.9969	778.9411	821.1058
15	0.1714	39.3466	747.5861	768.1041
16	0.1675	42.2890	803.4918	809.9483
17	0.1618	39.9467	758.9879	799.0965
18	0.1628	43.0101	817.1924	860.3653
19	0.1665	40.6985	773.2708	814.1358
20	0.1704	38.9821	740.6591	779.8116
Sum	3.31	818.52	15551.79	16319.41
Mean	0.17	40.93	777.59	815.97
SD	0.00	1.34	25.44	27.51

Table A.4. WSN lifetime for LEACH-SM SM without spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	0
The ratio of the cluster nodes that become spares	50%

LEACH-SM				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1685	52.4084	995.7597	1448.3000
2	0.1665	61.6986	1172.3000	1234.1000
3	0.1618	68.8804	1308.7000	1377.8000
4	0.1654	61.9616	1177.3000	1439.4000
5	0.1649	66.3348	1260.4000	1326.9000
6	0.1716	58.7336	1115.9000	1474.8000
7	0.1696	65.7928	1250.1000	1395.0000
8	0.1678	62.8052	1193.3000	1251.3000
9	0.1689	80.4807	1529.1000	1609.8000
10	0.1696	75.4153	1432.9000	1508.5000
11	0.1653	72.5149	1377.8000	1445.5000
12	0.1634	59.1692	124.2000	1483.5000
13	0.1628	61.7422	1173.1000	1435.0000
14	0.1643	58.9030	1119.2000	1478.2000
15	0.1681	85.5040	1624.6000	1701.2000
16	0.1658	91.9309	1746.7000	1834.8000
17	0.1670	75.9090	1442.3000	1517.3000
18	0.1650	62.7294	1191.9000	1254.8000
19	0.1626	61.2550	1163.8000	1225.3000
20	0.1720	69.5595	1321.6000	1391.4000
Sum	3.33	1353.73	24720.96	28832.90
Mean	0.17	67.69	1236.05	1441.65
SD	0.00	9.97	320.76	153.50

Table A.5. WSN lifetime for LEACH.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	10
The ratio of the cluster nodes that become spares	25%

LEACH				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1716	110.0478	2090.9000	2201.1000
2	0.1683	113.5233	2186.9000	2190.6000
3	0.1635	122.7517	2332.3000	2185.2000
4	0.1661	117.3557	2229.8000	2157.3000
5	0.1715	106.2961	2019.6000	2229.1000
6	0.1622	117.9930	2241.9000	2160.0000
7	0.1655	113.8547	2163.2000	2177.3000
8	0.1628	116.7779	2218.8000	2135.7000
9	0.1638	117.9378	2240.8000	2158.9000
10	0.1655	113.6975	2160.3000	2174.1000
11	0.1648	117.4959	2232.4000	2150.1000
12	0.1718	101.6402	1931.2000	2133.0000
13	0.1639	104.9544	1994.1000	2199.3000
14	0.1672	106.5164	2023.8000	2130.5000
15	0.1639	102.0852	1939.6000	2241.9000
16	0.1633	107.8699	2049.5000	2157.6000
17	0.1703	100.2636	1905.0000	2205.4000
18	0.1695	99.2485	1885.7000	1985.1000
19	0.1617	106.0993	2015.9000	2122.1000
20	0.1674	103.1374	1959.6000	2162.9000
Sum	3.32	2199.55	41821.30	43257.20
Mean	0.17	109.98	2091.07	2162.86
SD	0.00	7.06	135.16	52.83

Table A.6. WSN lifetime for LEACH-SM SM without spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	10
The ratio of the cluster nodes that become spares	25%

LEACH-SM				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1664	126.0657	2395.2000	2521.5000
2	0.1691	108.6967	2065.2000	2374.1000
3	0.1623	146.7786	2788.8000	2935.7000
4	0.1696	114.7852	2180.9000	2395.9000
5	0.1632	129.7452	2465.2000	2595.1000
6	0.1670	124.7953	2371.1000	2496.1000
7	0.1693	135.0222	2565.4000	2790.6000
8	0.1640	128.0244	2432.5000	2660.7000
9	0.1688	120.4743	2289.0000	2405.7000
10	0.1689	156.3468	2970.6000	3127.1000
11	0.1641	122.7984	2333.2000	2456.1000
12	0.1676	133.8594	2543.3000	2677.4000
13	0.1689	115.3604	2191.8000	2307.4000
14	0.1628	133.2521	2531.8000	2665.2000
15	0.1638	144.2746	2741.2000	2885.7000
16	0.1680	149.2899	2836.5000	2986.0000
17	0.1672	144.8725	2752.6000	2897.6000
18	0.1653	167.0055	3173.1000	3340.3000
19	0.1698	150.8890	2866.9000	2817.9000
20	0.1612	170.8666	3246.5000	3417.5000
Sum	3.33	2723.20	51740.80	54753.60
Mean	0.17	136.16	2587.04	2737.68
SD	0.00	17.21	327.05	316.10

Table A.7. WSN lifetime for LEACH.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	10
The ratio of the cluster nodes that become spares	50%

LEACH				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1692	104.5327	1986.1000	2090.8000
2	0.1611	113.4333	2155.2000	2268.8000
3	0.1646	112.8535	2144.2000	2257.2000
4	0.1638	104.8860	1992.8000	2097.9000
5	0.1719	99.5366	1891.2000	1990.9000
6	0.1656	107.1463	2035.8000	2143.1000
7	0.1675	101.5477	1929.4000	2231.1000
8	0.1644	106.9741	2032.5000	2199.6000
9	0.1716	99.9760	1899.5000	1999.7000
10	0.1721	106.2539	2018.8000	2325.3000
11	0.1646	103.5317	1967.1000	2170.8000
12	0.1700	106.5982	2025.4000	2182.1000
13	0.1665	107.0828	2034.6000	2141.8000
14	0.1643	112.5455	2138.4000	2249.1000
15	0.1689	109.9002	2088.1000	2298.2000
16	0.1684	106.8971	2031.0000	2138.1000
17	0.1709	101.7923	1934.1000	2036.0000
18	0.1681	103.1059	1959.0000	2262.3000
19	0.1708	108.1201	2054.3000	2162.6000
20	0.1681	100.5422	1910.3000	2011.0000
Sum	3.35	2117.26	40227.80	43256.40
Mean	0.17	105.86	2011.39	2162.82
SD	0.00	4.18	79.46	101.25

Table A.8. WSN lifetime for LEACH-SM SM without spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	10
The ratio of the cluster nodes that become spares	50%

LEACH-SM				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1706	250.2616	4755.0000	3805.4000
2	0.1670	204.9435	3893.9000	3899.0000
3	0.1702	190.0866	3611.6000	3801.9000
4	0.1703	181.3220	3445.1000	3626.6000
5	0.1620	179.4875	3410.3000	3589.9000
6	0.1717	154.7155	2939.6000	3094.5000
7	0.1666	227.4372	4321.3000	4548.9000
8	0.1619	264.0178	5016.3000	3880.5000
9	0.1690	143.4596	2725.7000	2869.4000
10	0.1718	237.2074	4506.9000	4744.3000
11	0.1704	193.2528	3671.8000	3865.2000
12	0.1618	263.1526	4999.9000	3863.2000
13	0.1653	190.0051	3610.1000	3800.3000
14	0.1635	275.3416	5231.5000	3805.0000
15	0.1679	224.4115	4263.8000	4480.4000
16	0.1623	237.5200	4512.9000	4750.6000
17	0.1705	157.8227	2998.6000	3156.6000
18	0.1688	194.6887	3699.1000	3893.9000
19	0.1667	163.0272	3097.5000	3260.7000
20	0.1676	184.5515	3506.5000	3691.2000
Sum	3.35	4116.71	78217.40	76427.50
Mean	0.17	205.84	3910.87	3821.38
SD	0.00	39.37	747.99	512.89

Table A.9. WSN lifetime for LEACH.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	20
The ratio of the cluster nodes that become spares	25%

LEACH				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1670	167.2562	3177.9000	3645.3000
2	0.1680	162.6909	3091.1000	3554.0000
3	0.1637	163.1652	3100.1000	3763.5000
4	0.1636	169.3388	3217.4000	3386.9000
5	0.1632	162.7798	3092.8000	3655.8000
6	0.1640	169.4203	3219.0000	3688.6000
7	0.1690	167.2636	3178.0000	3301.4000
8	0.1658	166.0556	3155.1000	3215.3000
9	0.1614	164.0916	3117.7000	3682.0000
10	0.1637	168.8719	3208.6000	3377.6000
11	0.1637	168.4642	3200.8000	3369.4000
12	0.1652	159.6745	3033.8000	3693.7000
13	0.1700	168.2493	3196.7000	3665.2000
14	0.1626	165.9815	3153.6000	3319.8000
15	0.1698	159.1335	3023.5000	3582.8000
16	0.1689	167.7824	3187.9000	3355.8000
17	0.1664	159.6449	3033.3000	3593.1000
18	0.1701	160.8381	3055.9000	3616.9000
19	0.1614	170.6876	3243.1000	3413.9000
20	0.1667	165.7740	3149.7000	3315.6000
Sum	3.31	3307.16	62836.00	70196.60
Mean	0.17	165.36	3141.80	3509.83
SD	0.00	3.62	68.87	168.35

Table A.10. WSN lifetime for LEACH-SM SM without spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	20
The ratio of the cluster nodes that become spares	25%

LEACH-SM				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1715	206.6320	3926.0000	4132.8000
2	0.1634	240.1010	4561.9000	4402.2000
3	0.1633	273.4737	5196.0000	4469.6000
4	0.1646	223.4110	4244.8000	4468.4000
5	0.1720	257.4284	4891.1000	4448.7000
6	0.1677	224.1224	4258.3000	4482.6000
7	0.1624	256.1463	4866.8000	5123.1000
8	0.1621	216.6519	4116.4000	4333.2000
9	0.1692	217.6747	4135.8000	4353.7000
10	0.1718	216.9484	4122.0000	4339.1000
11	0.1680	228.4061	4339.7000	4568.3000
12	0.1615	195.6041	3716.5000	3912.2000
13	0.1640	221.1209	4201.3000	4422.6000
14	0.1623	229.0435	4351.8000	4581.0000
15	0.1712	222.8848	4234.8000	4457.9000
16	0.1615	227.1536	4315.9000	4543.2000
17	0.1679	197.0419	3743.8000	3941.0000
18	0.1631	209.8633	3987.4000	4197.4000
19	0.1630	204.1196	3878.3000	4082.6000
20	0.1618	271.9544	5167.1000	5439.2000
Sum	3.31	4539.78	86255.70	88698.80
Mean	0.17	226.99	4312.79	4434.94
SD	0.00	22.50	427.45	352.04

Table A.11. WSN lifetime for LEACH.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	20
The ratio of the cluster nodes that become spares	50%

LEACH				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1631	175.2982	3330.7000	3406.1000
2	0.1699	177.5933	3374.3000	3582.0000
3	0.1686	170.7223	3243.7000	3424.6000
4	0.1713	166.1247	3156.4000	3624.7000
5	0.1623	177.6224	3374.8000	3553.6000
6	0.1655	168.4780	3201.1000	3369.7000
7	0.1620	171.1654	3252.1000	3423.5000
8	0.1635	186.1131	3536.1000	3722.4000
9	0.1633	184.8711	3512.6000	3697.6000
10	0.1664	177.4844	3372.2000	3579.9000
11	0.1668	174.6445	3318.2000	3493.1000
12	0.1681	178.0001	3382.0000	3560.2000
13	0.1639	167.8516	3189.2000	3357.2000
14	0.1672	170.3498	3236.6000	3507.2000
15	0.1639	163.2630	3102.0000	3265.4000
16	0.1633	172.5143	3277.8000	3450.5000
17	0.1703	160.3497	3046.6000	3307.2000
18	0.1695	158.7262	3015.8000	3674.7000
19	0.1617	169.6826	3224.0000	3393.8000
20	0.1674	164.9457	3134.0000	3799.1000
Sum	3.32	3435.80	65280.20	70192.50
Mean	0.17	171.79	3264.01	3509.63
SD	0.00	7.34	139.46	146.10

Table A.12. WSN lifetime for LEACH-SM SM without spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	20
The ratio of the cluster nodes that become spares	50%

LEACH-SM				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1718	302.6009	5749.4000	6052.2000
2	0.1709	330.4699	6278.9000	6609.6000
3	0.1664	305.8475	5811.1000	6117.1000
4	0.1716	323.0541	6138.0000	6061.3000
5	0.1688	285.5032	5424.6000	6710.2000
6	0.1645	403.3928	7664.5000	6028.0000
7	0.1613	467.4327	8881.2000	6358.8000
8	0.1682	351.8020	6684.2000	6066.2000
9	0.1652	325.8142	6190.5000	6516.4000
10	0.1694	324.8554	6172.3000	6427.3000
11	0.1649	241.5679	4589.8000	4831.5000
12	0.1625	343.6164	6528.7000	6802.5000
13	0.1689	241.0694	4580.3000	4821.6000
14	0.1628	288.4456	5480.5000	6769.1000
15	0.1638	322.5155	6127.8000	6410.5000
16	0.1680	342.0339	6498.6000	6840.8000
17	0.1672	327.1116	6215.1000	6542.4000
18	0.1653	400.0921	7601.8000	6002.0000
19	0.1698	349.0465	6631.9000	5981.1000
20	0.1612	409.0173	7771.3000	6080.5000
Sum	3.33	6685.29	127020.50	124029.10
Mean	0.17	334.26	6351.03	6201.46
SD	0.00	54.85	1042.15	554.11

Table A.13. WSN lifetime for LEACH.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	30
The ratio of the cluster nodes that become spares	25%

LEACH				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1669	281.5616	5349.7000	5131.4000
2	0.1628	270.5420	5140.3000	4411.0000
3	0.1700	265.1251	5037.4000	5302.7000
4	0.1626	286.2647	5439.0000	4725.5000
5	0.1618	280.2025	5323.8000	4604.2000
6	0.1681	273.2505	5191.8000	4465.2000
7	0.1630	287.8976	5470.1000	4758.1000
8	0.1649	258.8184	4917.6000	5176.5000
9	0.1641	275.6754	5237.8000	5313.7000
10	0.1720	266.4354	5062.3000	4328.9000
11	0.1689	260.6762	4952.8000	5213.7000
12	0.1630	290.3519	5516.7000	4607.2000
13	0.1632	278.8141	5297.5000	4676.4000
14	0.1706	258.5251	4912.0000	4970.7000
15	0.1665	281.5127	5348.7000	4690.4000
16	0.1676	275.3527	5231.7000	4507.2000
17	0.1703	249.7055	4744.4000	4964.3000
18	0.1623	264.0593	5017.1000	5281.3000
19	0.1677	282.6763	5370.8000	5353.7000
20	0.1631	277.3083	5268.9000	4646.3000
Sum	3.32	5464.76	103830.40	97128.40
Mean	0.17	273.24	5191.52	4856.42
SD	0.00	11.12	211.32	338.33

Table A.14. WSN lifetime for LEACH-SM SM without spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	30
The ratio of the cluster nodes that become spares	25%

LEACH-SM				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1702	261.6247	4970.9000	6232.7000
2	0.1669	268.5962	5103.3000	6372.1000
3	0.1659	337.0604	6404.1000	6741.4000
4	0.1655	262.1918	4981.6000	6144.0000
5	0.1670	285.9616	5433.3000	5719.4000
6	0.1659	270.7963	5145.1000	5416.1000
7	0.1652	315.4221	5993.0000	6108.6000
8	0.1713	283.0772	5378.5000	5691.7000
9	0.1672	290.6452	5522.3000	5813.1000
10	0.1689	285.3652	5421.9000	5757.5000
11	0.1631	270.6203	5141.8000	5412.6000
12	0.1673	268.8798	5108.7000	6370.8000
13	0.1662	319.9102	6078.3000	6378.4000
14	0.1653	323.0586	6138.1000	6461.3000
15	0.1677	322.2471	6122.7000	6445.1000
16	0.1643	326.2560	6198.9000	6525.3000
17	0.1692	291.8772	5545.7000	5837.7000
18	0.1709	305.5270	5805.0000	6110.7000
19	0.1658	352.0400	6688.8000	7041.0000
20	0.1622	307.0719	5834.4000	6141.6000
Sum	3.34	5948.23	113016.40	122721.10
Mean	0.17	297.41	5650.82	6136.06
SD	0.00	26.95	512.10	427.23

Table A.15. WSN lifetime for LEACH.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	30
The ratio of the cluster nodes that become spares	50%

LEACH				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1689	226.7033	4307.4000	4834.2000
2	0.1670	228.9510	4350.1000	4879.2000
3	0.1719	224.8302	4271.8000	4996.8000
4	0.1698	230.0951	4371.8000	4602.1000
5	0.1642	237.5064	4512.6000	4950.3000
6	0.1669	223.1495	4239.8000	4963.2000
7	0.1686	234.7018	4459.3000	4994.2000
8	0.1639	242.8927	4615.0000	4828.0000
9	0.1698	224.6986	4269.3000	4994.1000
10	0.1713	237.4760	4512.0000	4949.7000
11	0.1697	232.4643	4416.8000	4649.5000
12	0.1631	232.9300	4425.7000	4658.8000
13	0.1679	238.0126	4522.2000	4960.4000
14	0.1641	230.5810	4381.0000	4911.8000
15	0.1675	227.6449	4325.3000	4853.1000
16	0.1683	226.6526	4306.4000	4933.2000
17	0.1690	235.3701	4472.0000	4907.6000
18	0.1662	229.8926	4368.0000	4598.0000
19	0.1657	226.7539	4308.3000	4935.2000
20	0.1676	230.6013	4381.4000	4912.2000
Sum	3.35	4621.91	87816.20	97311.60
Mean	0.17	231.10	4390.81	4865.58
SD	0.00	5.26	99.96	132.14

Table A.16. WSN lifetime for LEACH-SM SM without spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	30
The ratio of the cluster nodes that become spares	50%

LEACH-SM				
Obs.	Total time spend by a node in Setup phase during WSN lifetime	Total time a node serve as a cluster head during WSN lifetime	Total time a node serve as a Regular Node during WSN lifetime	WSN Lifetime
1	0.1615	537.2395	10208.0000	8045.0000
2	0.1656	374.1804	7109.4000	8453.8000
3	0.1647	445.5092	8464.7000	8990.3000
4	0.1621	567.6947	10786.0000	8354.0000
5	0.1670	366.8501	6970.2000	8337.2000
6	0.1682	451.2500	8573.7000	9025.2000
7	0.1686	523.4394	9945.3000	8469.0000
8	0.1685	435.8401	8281.0000	8717.0000
9	0.1612	466.0726	8855.4000	8321.6000
10	0.1662	449.6604	8543.5000	8993.4000
11	0.1698	557.5700	10594.0000	8552.0000
12	0.1664	506.0552	9615.0000	8117.0000
13	0.1693	366.9614	6972.3000	8339.0000
14	0.1632	584.5119	11106.0000	8589.0000
15	0.1672	408.2603	7756.9000	8165.4000
16	0.1682	460.0585	8741.1000	9201.3000
17	0.1624	447.4633	8501.8000	8949.4000
18	0.1697	403.8459	7673.1000	8077.1000
19	0.1704	418.3749	7949.1000	8367.7000
20	0.1708	487.6586	9265.5000	9553.3000
Sum	3.33	9258.50	175912.00	171617.70
Mean	0.17	462.92	8795.60	8580.89
SD	0.00	66.00	1254.00	414.25

Table A.17. WSN lifetime for LEACH-SM with spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	0
The ratio of the cluster nodes that become spares	25%

LEACH-SM				First Replacement	
Obs.	Number of Frames per Round	WSN Lifetime	Lifetime of Spares	Number of Frames per Round	WSN Lifetime
1	28820	1014.1000	6928.0		
2	28459	1001.4000	6924.9		
3	36238	1075.1000	7146.1		
4	30638	998.1000	6982.2		
5	35516	949.7000	7118.3		
6	26819	973.6927	6875.4		
7	32708	958.9000	7047.5		
8	31628	913.9000	7012.2		
9	36176	1072.9000	7136.8		
10	30725	1081.1000	6989.8		
11	30795	1083.6000	6992.1		
12	33319	1172.4000	7062.7		
13	27937	983.0288	6903.5		
14	37835	1331.2000	7189.8		
15	29299	1030.9000	6945.5		
16	28738	911.2000	6931.3		
17	25720	905.0294	6843.7		
18	33499	1178.7000	7067.6		
19	31551	1010.2000	7013.7		
20	27492	967.3681	6895.9		
Sum	623912.00	20612.52	140007.00		
Mean	31195.60	1030.63	7000.35		
SD	3420.73	104.87	97.41		

Note: No replacement possible in this case.

Table A.18. WSN lifetime for LEACH-SM with spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	0
The ratio of the cluster nodes that become spares	50%

LEACH-SM				First Replacement	
Obs.	Number of Frames per Round	WSN Lifetime	Lifetime of Spares	Number of Frames per Round	WSN Lifetime
1	36649	1172.5000	6502.1	31675	2685.8000
2	41322	1321.9000	6620.1	35176	2547.3000
3	35729	1143.0000	6479.3	30990	2634.5000
4	55997	1791.3000	7001	46263	3271.3000
5	40914	1308.9000	6608.6	34807	2422.4000
6	39228	1254.9000	6568.3	33685	2632.6000
7	40646	1300.3000	6605.5	34822	2514.3000
8	55005	1759.6000	6968.7	44941	3197.3000
9	50287	1608.7000	6856.4	42293	2961.7000
10	38804	1441.4000	6559.3	33453	2311.6000
11	33569	1473.9000	6423.6	29263	2010.1000
12	54237	1705.0000	6949.2	44430	3156.4000
13	44956	1458.2000	6714.4	37979	2653.2000
14	40444	1293.8000	6600.5	34675	2403.1000
15	37477	1198.9000	6525.9	32447	2237.0000
16	53617	1735.2000	6937.7	44377	3134.8000
17	58353	1896.7000	7058.2	47610	3389.8000
18	45495	1485.4000	6727.6	38341	2682.0000
19	38691	1257.8000	6554.1	33246	2301.4000
20	38017	1226.2000	6539.7	32868	2267.7000
Sum	879437.00	28833.60	133800.20	743341.00	53414.30
Mean	43971.85	1441.68	6690.01	37167.05	2670.72
SD	7743.02	232.44	198.07	5709.47	392.01

Note: No replacement possible in this case.

Table A.19. WSN lifetime for LEACH-SM with spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	10
The ratio of the cluster nodes that become spares	25%

LEACH-SM				First Replacement	
Obs.	Number of Frames per Round	WSN Lifetime	Lifetime of Spares	Number of Frames per Round	WSN Lifetime
1	33247	2944.7000	17779		
2	28902	2539.9000	17464		
3	30453	2667.3000	17570		
4	27410	2417.8000	17345		
5	34097	3020.0000	17820		
6	30156	2651.0000	17539		
7	27241	2712.8000	17336		
8	27668	2450.6000	17364		
9	25995	2702.4000	17239		
10	35880	3177.9000	17950		
11	26847	2577.9000	17315		
12	30363	2659.3000	17554		
13	38375	3368.9000	18140		
14	34059	3016.6000	17819		
15	38499	3409.9000	18138		
16	25749	2280.6000	17226		
17	26905	2383.0000	17312		
18	33764	2990.5000	17793		
19	25113	2224.3000	17180		
20	27666	2450.4000	17370		
Sum	608389.00	54645.80	351253.00		
Mean	30419.45	2732.29	17562.65		
SD	4203.31	344.77	300.93		

Note: No replacement possible in this case.

Table A.20. WSN lifetime for LEACH-SM with spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	10
The ratio of the cluster nodes that become spares	50%

LEACH-SM				First Replacement	
Obs.	Number of Frames per Round	WSN Lifetime	Lifetime of Spares	Number of Frames per Round	WSN Lifetime
1	38633	3829.7000	17660	33296	6199.4000
2	38534	3821.1000	17644	33045	6169.2000
3	53038	3871.1000	18659	44181	7378.9000
4	37136	3200.6000	17553	32072	6404.9000
5	34163	2974.4000	17341	29622	5597.5000
6	38152	3288.2000	17624	32883	6492.3000
7	39725	3423.8000	17747	34379	6696.8000
8	46796	4033.2000	18223	39478	7435.7000
9	54082	3861.1000	18723	44679	8411.8000
10	56652	4782.6000	18899	46416	7083.0000
11	56651	4782.5000	18902	46527	7052.5000
12	55911	4718.7000	18858	46252	7805.0000
13	48261	4159.4000	18335	40847	7679.9000
14	41302	3559.7000	17843	35325	6604.3000
15	53267	3890.9000	18668	44117	8150.1000
16	34291	2955.5000	17360	29894	6502.0000
17	44372	3824.3000	18061	37803	7002.4000
18	50618	3862.6000	18482	42149	7995.2000
19	57034	3815.5000	18917	46372	7902.1000
20	43836	3778.1000	18027	37472	7007.7000
Sum	922454.00	76433.00	363526.00	776809.00	141570.70
Mean	46122.70	3821.65	18176.30	38840.45	7078.54
SD	8070.38	522.54	557.02	5981.64	755.92

Note: No replacement possible in this case.

Table A.21. WSN lifetime for LEACH-SM with spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	20
The ratio of the cluster nodes that become spares	25%

LEACH-SM				First Replacement	
Obs.	Number of Frames per Round	WSN Lifetime	Lifetime of Spares	Number of Frames per Round	WSN Lifetime
1	25641	4170.9000	27076		
2	34941	4066.0000	28141		
3	26368	3872.1000	27156		
4	37114	5168.6000	28379		
5	29179	4063.6000	27497		
6	28244	4933.4000	27376		
7	30818	4291.8000	27659		
8	36155	5035.0000	28263		
9	36246	5047.7000	28285		
10	28352	3948.4000	27393		
11	29857	4158.0000	27539		
12	30834	4294.1000	27673		
13	31553	4394.2000	27763		
14	36952	5146.0000	28359		
15	25744	3585.2000	27114		
16	35897	4999.1000	28227		
17	35649	4964.6000	28209		
18	31236	4350.0000	27730		
19	30110	4193.2000	27576		
20	28766	4006.1000	27434		
Sum	629656.00	88688.00	554849.00		
Mean	31482.80	4434.40	27742.45		
SD	3883.84	492.80	437.59		

Note: No replacement possible in this case.

Table A.22. WSN lifetime for LEACH-SM with spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	20
The ratio of the cluster nodes that become spares	50%

LEACH-SM				First Replacement	
Obs.	Number of Frames per Round	WSN Lifetime	Lifetime of Spares	Number of Frames per Round	WSN Lifetime
1	48185	6809.0000	30027	40358	10512.0000
2	50520	6139.0000	30293	42090	11087.0000
3	39887	5636.5000	29078	34035	10446.0000
4	48139	6802.5000	30032	40498	11525.0000
5	36883	5212.0000	28756	31929	10723.9000
6	43497	6146.6000	29492	36833	11351.0000
7	45026	6362.6000	29664	37958	11726.0000
8	38051	5377.0000	28870	32626	9987.4000
9	48858	6904.1000	30105	40893	12683.0000
10	50475	6132.6000	30302	42295	10109.0000
11	51747	6312.3000	30423	42794	11360.0000
12	47640	6732.0000	29987	40306	12828.0000
13	41686	5890.7000	29308	35742	11141.0000
14	33343	6011.7000	28370	29258	11846.2000
15	53129	6007.6000	30596	44097	11739.0000
16	47992	6781.7000	30017	40408	12492.0000
17	47335	6358.9000	29934	39795	12312.0000
18	50334	6012.7000	30294	42322	13093.0000
19	54212	6050.7000	30719	44876	11002.0000
20	53182	6350.1000	30609	44272	11771.0000
Sum	930121.00	124030.30	596876.00	783385.00	229734.50
Mean	46506.05	6201.52	29843.80	39169.25	11486.73
SD	5860.86	467.10	664.77	4425.62	892.78

Note: No replacement possible in this case.

Table A.23. WSN lifetime for LEACH-SM with spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	30
The ratio of the cluster nodes that become spares	25%

LEACH-SM				First Replacement	
Obs.	Number of Frames per Round	WSN Lifetime	Lifetime of Spares	Number of Frames per Round	WSN Lifetime
1	29371	6023.7000	40489		
2	26870	5510.7000	40109		
3	33674	6906.1000	41206		
4	28386	5821.6000	40342		
5	26650	5465.6000	40063		
6	26393	5412.9000	40043		
7	34756	7128.0000	41369		
8	34683	6113.1000	41385		
9	30029	6158.6000	40598		
10	27544	5649.0000	40204		
11	30074	6167.8000	40594		
12	38078	7809.3000	41920		
13	30342	6222.8000	40648		
14	28208	6360.1000	40288		
15	28023	5747.2000	40260		
16	28317	5807.5000	40350		
17	35920	6166.7000	41607		
18	28848	5916.4000	40388		
19	30423	6239.4000	40678		
20	33139	6096.4000	41150		
Sum	609728.00	122722.90	813691.00		
Mean	30486.40	6136.15	40684.55		
SD	3388.17	583.51	557.01		

Note: No replacement possible in this case.

Table A.24. WSN lifetime for LEACH-SM with spares.

Nodes	100
Number of clusters per round (K)	5
Duration of a Nap interval of a cluster head	30
The ratio of the cluster nodes that become spares	50%

LEACH-SM				First Replacement	
Obs.	Number of Frames per Round	WSN Lifetime	Lifetime of Spares	Number of Frames per Round	WSN Lifetime
1	35885	7027.8000	39679	31006	13100.0000
2	42255	8275.3000	40716	36263	15377.0000
3	35234	8470.3000	39568	30426	12859.0000
4	37347	7314.1000	39930	32317	15643.0000
5	57112	11185.0000	43048	47197	20428.0000
6	35638	6979.4000	39666	31003	14510.0000
7	44314	8678.5000	41044	37880	16097.0000
8	39448	7725.5000	40261	33967	14378.0000
9	58262	11410.0000	43216	47817	20775.0000
10	55708	10910.0000	42775	45433	19807.0000
11	45918	8992.6000	41277	38899	16611.0000
12	33546	6569.7000	39341	29361	12320.0000
13	47606	9323.2000	41560	40356	17227.0000
14	35011	6856.6000	39565	30493	12828.0000
15	43640	8546.5000	40918	37165	15825.0000
16	40267	7885.9000	40373	34448	14632.0000
17	48639	9525.5000	41684	40680	17492.0000
18	47490	9300.5000	41538	40221	17177.0000
19	36771	7201.3000	39864	32053	13479.0000
20	48163	9432.3000	41612	40355	17335.0000
Sum	868254.00	171610.00	817635.00	737340.00	317900.00
Mean	43412.70	8580.50	40881.75	36867.00	15895.00
SD	7644.67	1449.13	1199.75	5717.26	2507.53

Note: No replacement possible in this case.

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