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Phil. Trans. R. Soc. A 2012 **370**, 52-67

doi: 10.1098/rsta.2011.0195

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Energy management in sensor networks

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This paper presents a holistic view of energy management in sensor networks. We first discuss hardware designs that support the life cycle of energy, namely: (i) energy harvesting, (ii) energy storage and (iii) energy consumption and control. Then, we discuss individual software designs that manage energy consumption in sensor networks. These energy-aware designs include media access control, routing, localization and time-synchronization. At the end of this paper, we present a case study of the VigilNet system to explain how to integrate various types of energy management techniques to achieve collaborative energy savings in a large-scale deployed military surveillance system.

Keywords: energy management; energy harvesting; energy storage

1. Introduction

Wireless sensor networks (WSNs) are being used in many application areas, including agriculture, medicine, transportation, environmental science and the military. Today, most WSNs rely on batteries to provide energy. In some systems, energy harvesting is used to completely eliminate batteries or to supplement them. Most WSNs optimize across many factors, including form factor, cost and energy use. This gives rise to one of the key problems in WSNs, i.e. how to provide energy management in order to increase the working lifetime of the system while meeting functional and sensing coverage requirements. This paper discusses this issue.

The hardware components of a WSN typically include various mechanisms to control the use of energy. In addition, the hardware includes batteries and/or energy harvesting devices. Section 2 discusses the hardware issues. In WSNs, energy is consumed by computation, communication, sensing and idling states. In almost every software component that supports any of these states, there is often an attempt to be highly energy-efficient. We categorize all such attempts as energy management in the small, as it involves individual protocols whose functional purpose is not energy management. In §3, we provide a set of examples of energy management in the small. Since energy management is so important,

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One contribution of 11 to a Theme Issue ‘Sensor network algorithms and applications’.

many WSNs include additional modules whose sole purpose is to manage energy. We refer to these components as energy management in the large. Examples of such solutions are presented in §4.

As stated above, energy management strives to increase the lifetime of a WSN. However, it is not clear how to measure lifetime. For example, given a single device (node), it is easy to define lifetime as the length of time from initially turning the node on until it runs out of energy. However, it is more complicated for a WSN. For the entire system, should the lifetime be the time at which the *first* node runs out of energy? This seems much too restrictive, especially for a large WSN. Should lifetime be defined as the time at which half the nodes die, a kind of system half-life? The problem is that such a definition ignores the semantics of the WSN. It is possible that the WSN, ceases to function long before half the nodes are dead. Ideally, the lifetime of a WSN should be defined as the time at which it stops providing its key functionality. However, it is extremely difficult to determine that point in time. This leaves us without a clear definition of lifetime for a WSN, and care must be taken to understand a particular solution's definition of lifetime.

2. Hardware properties

We approach the hardware side of energy management by discussing ways to scavenge energy and how it can be stored, and then give details on how it is consumed and the levels of controls that are possible for the different components in a sensor node.

(a) *Energy harvesting*

Owing to the small form factor and low-cost requirements, the sensor nodes (e.g. the Mica series) used in many applications are normally equipped with limited energy sources (e.g. 2200 mA h at 3 V for two AA batteries). In many applications, hazardous or inaccessible environments preclude manual battery replacement. Without renewable energy resources, a sensor node can sometimes live for less than 1 day at 100 per cent duty cycle. To ensure sustainable operation, environmental energy harvesting has been pursued by the research community as the right solution for long-term applications.

Basically, energy harvesting converts ambient energy into usable electrical energy. Many technologies have been developed for extracting energy from the environment, including solar [1–6], wind [7], kinetic [8], radio frequency (RF) [9], vibrational [10] and piezoelectric strain [11,12] energy. With these energy harvesting technologies, researchers have designed various types of platforms to collect ambient energy from human activity or environments. Table 1 lists the power densities achievable by various types of energy harvesting technologies. By using the photovoltaic effect, which converts light to electrical power, solar-cell-based energy harvesting techniques provide orders of magnitude higher power density than other technologies. Because of this, most existing energy harvesting systems used in sensor networks are based on solar cells, such as Helimote [2], Prometheus [6], Trio [1], AmbiMax [7], PicoNodes [13], PUMA [14] and TwinStar [15]. To design a highly efficient solar-based harvesting system,

Table 1. Achievable power density by different energy harvesting technologies.

harvesting technology	power density
solar cells (outdoors at noon)	15 mW cm ⁻²
piezoelectric (shoe inserts)	330 W cm ⁻³
vibration (small microwave oven)	116 W cm ⁻³
thermoelectric (10 °C gradient)	40 W cm ⁻³
acoustic noise (100 dB)	960 nW cm ⁻³

these solar-based designs need to employ a maximum power point tracker (MPPT). It searches for an operating point where the product of the current (I) and voltage (V) achieves a maximum value.

(b) *Energy storage*

According to the type of energy storage used, the energy subsystem can be separated into four categories: (i) rechargeable battery-based storage, (ii) energy storage combining ultracapacitors and rechargeable batteries, (iii) capacitor-based energy storage, and (iv) non-conventional energy storage.

- In rechargeable battery designs, such as Helimote [2], the energy harvesting panel is directly connected to its battery. The typical types of rechargeable battery [16] are Li-ion, NiCAD and NiMH. Although rechargeable-based energy harvesting and storage systems have been effective in prolonging the lifetime of sensor nodes, they have inherent limitations, because (i) rechargeable batteries have limited recharge cycles due to cyclic memory and crystal formation (e.g. a Li-ion battery has a 500 cycle limit and NiMH a 300 cycle limit), and (ii) sophisticated recharging circuits and electrochemical conversion could reduce energy efficiency to as low as 6 per cent, according to the Natural Resources Defense Council [17].
- In designs that combine ultracapacitors and rechargeable batteries, such as Prometheus [6], the solar energy is first stored in the primary energy buffer, which consists of one or more ultracapacitors. The rechargeable batteries are then used as the secondary energy buffer. This design inherits both the advantages and limitations of batteries and capacitors. On the one hand, using capacitors as energy buffers can reduce the number of recharges, leading to a longer battery lifetime. On the other hand, it is difficult to predict remaining energy because of the inclusion of batteries, and the lifetime of the energy storage subsystem is decided by the shelf time of the batteries (of the order of a few years).
- Compared with rechargeable batteries, capacitors possess a set of advantages: they (i) have more than one million recharge cycles; (ii) have predictable remaining energy independent of discharge modes; (iii) are robust to temperature changes, shock and vibration; and (iv) have high charging and discharging efficiency. Furthermore, recent advances in ultracapacitor technology [18,19] make it possible to use ultracapacitors as the only energy storage device. Although ultracapacitor-based designs have

many advantages, they impose a major challenge: the energy leakage of ultracapacitors is high when they reach their full capacity. Recently, two capacitor-based energy harvesting and storage systems—TwinStar [15] and eShare [20]—have been proposed. The TwinStar system provides local leakage-aware energy control, and the eShare system supports global leakage-aware energy sharing.

- A few non-conventional storage methods are also used as energy supplies, such as microelectromechanical fuel cells, micro heat engines and radioactive energy cells. Owing to limiting factors such as cost, size, energy density and environmental concerns, these storage methods are adopted in limited scenarios and are not widely used in WSNs.

(c) Energy consumption and controls

Existing hardware designs for sensor nodes are based on either a modular or monolithic architecture. In the case of modular design, such as the Mica series [21], designers integrate off-the-shelf components together within one small printed circuit board, which allows flexible hardware/software configuration at the cost of higher energy consumption. In the case of monolithic design, designers try to eliminate layers between different components and customize hardware configuration based on specific functionality, leading to a much lower energy profile. It is common practice in sensor hardware design to enable fine-grained control of energy consumption in different parts of the system. Furthermore, each component can adjust its working mode to allow trade-offs between energy and performance. For example, the widely used Atmega128L microcontroller provides six types of working modes with different energy consumption rates. Similarly, the TI MSP430 offers up to seven low-power operational modes. These microcontrollers normally stop the central processing unit in the idle mode and further turn off the on-chip flash, analogue-to-digital converter and other input/output in the energy-save mode. In the energy-down mode, they stop everything except one interrupt line so that they can be awakened using an external source. Allowing multiple operational modes can significantly reduce the energy consumed during the idling period. For example, with less than 100 nA current draw, the TI MSP430 can retain the information in random access memory and wake itself up from the standby mode within less than 1 μ s.

In addition to adjusting operational modes, there are a few other approaches for energy saving. One is the reduction of the complexity of algorithms to reduce the run time of the microcontroller. Another technique is applying dynamic voltage scaling (DVS) to trade off between delay and performance. One can also execute computation-intensive tasks using customized application-specific integrated circuit components for better efficiency than can be achieved by a general-purpose microcontroller.

In addition to energy consumption in the microcontroller, RF chips are other major sources of energy consumption. Energy consumption in RF chips is significant in high-data-rate wireless networks. Typically, RF energy can be conserved through: (i) physical-layer transmission rate scaling [22,23]; (ii) link-layer optimization for better connectivity, reliability and stability [24–27]; (iii) network-layer enhancement for better forwarding and routing [28–31]; and (iv) application-layer improvements for both content-agnostic [32] and

content-centric data aggregation and inference [33–35]. From the hardware control perspective, energy can be reduced by turning off the radio as much as possible, because idle listening accounts for most energy in communication. This is because transmission time is usually very small (e.g. less than 1 ms to transmit a TinyOS packet using a Chipcon CC2420 radio), while the duration of idle listening for reception can be orders of magnitude longer. With a comparable current draw (19.7 mA when idle listening versus 17.4 mA when transmitting) and a three or four orders of magnitude longer duration waiting for reception, idle listening is a major energy drain. Another effective way to reduce energy consumption is through adaptive transmission power control (ATPC) [36]. In ATPC, each node builds a model for each of its neighbours, describing the correlation between transmission power and link quality. Using this model, ATPC employs a feedback-based transmission power control algorithm to dynamically maintain individual link quality over time.

Energy consumption in various types of sensor hardware differs significantly. For example, low-power temperature sensors such as TMP35/TMP36/TMP37 consume 0.135 mW and passive infrared (PIR) sensors such as KC7783 consume 0.88 mW, while magnetic sensors (Honeywell HMC1052) used in the extreme scale motes consume 19.4 mW, which is about 140 times as large as for the TM35 temperature sensors. For some high-end sensor types with more advanced functions, energy consumption is even higher. For example, MT9M001C12STM complementary metal–oxide–semiconductor digital image sensors consume as much as 363 mW. Therefore, to save energy at the sensor level, the most effective method is to selectively turn off sensors (especially high-end sensors) when possible. Energy saving strategies should adopt different schemes for different types of systems. For sampling systems such as Great Duck Island [37] and structural monitoring [38], because environmental phenomena, such as temperature, exist ubiquitously over space and continuously over time, the relatively static nature of these phenomena makes it sufficient to construct a data profile by sampling the environment within discrete time and space. Nodes can conserve energy by turning all sensors off most of the time and sampling briefly according to a predefined schedule. For event-driven systems such as surveillance systems [39], it is necessary to provide (almost) continuous monitoring to ensure 100 per cent detection. However, in these systems, it is not necessary to obtain a full data profile in the absence of the events of interest. To save energy, in event-driven systems, one should adopt a selective and incremental wake-up scheme. For example, low-power sensors such as a PIR at 0.88 mW are used for continuous monitoring. More energy-hungry sensors (e.g. magnetic sensors at 19.4 mW and image sensors) can be triggered by low-power sensors after initial detection to provide high-quality detection, tracking and classification.

3. Energy management in the small

Every protocol in a WSN consumes energy when it executes regardless of whether it is supporting general application functionality, communicating, operating system processing or sensing. Solutions for various functions (such as media access control (MAC), routing, etc.) are often tailored to try and save energy.

As examples, we discuss the special optimization techniques used by protocols that attempt to save energy. We point out various trade-offs that are made between accuracy/reliability and energy consumption.

(a) *Media access control protocols*

MAC protocols typically fall into a time-division multiple access (TDMA) or carrier-sensed multiple access (CSMA) class for WSNs. Here we consider only CSMA, the most prevalent class. While there are many variants to CSMA protocols, the main principles are: listen to see if the medium is busy; if not, then send the message; else back off and wait a random time; then try again. For WSNs, where energy is a key ingredient, CSMA protocols add a sleep-when-possible aspect to their logic. Without sleep states in the protocols, idle listening would consume a large portion of the available energy. Consequently, an explicit idea found in most CSMA protocols for WSNs is to keep the radio on only when involved with either sending or receiving. In addition, as collisions result in totally wasted energy, an implicit aspect of the protocols is to minimize collisions, which, in turn, also reduces energy consumption.

While the 802.11b DCF (distributed coordination function) protocol for wireless communications is not for WSNs, it does have several mechanisms for saving energy that are sometimes used in WSNs, including a doze mode. The basic protocol uses a request to send (RTS) and a clear to send (CTS) exchange to identify nodes that wish to communicate. Other nodes hearing this exchange can avoid collisions, thereby saving wasted energy. A variant of 802.11b called doze mode uses a beacon to start an interval. At the beginning of this time interval, nodes exchange ATIM (announcement traffic indication message) messages if they wish to communicate in the rest of the interval. Any node that is not either a sender or a receiver can go to sleep. Note that all RTS/CTS and ATIM messages consume energy. In 802.11b, data packets tend to be large and so this overhead is deemed acceptable. For many WSNs, packets are of the same approximate size as RTS/CTS and so such overhead is not acceptable.

S-MAC (Sensor media access control) [27] is a WSN protocol that divides time into an awake slot and a sleep slot. Typically, the awake slot is a small percentage of the time, e.g. 1–5%. In this protocol, the entire WSN radio system is asleep during the sleep slot and the entire system is awake during the awake slot. In other words, all communication is performed during the awake slot. In the awake slot, a fairly standard CSMA protocol runs that uses an RTS/CTS exchange. Consequently, in this awake slot, nodes not involved in an overheard exchange can temporarily go to sleep until that exchange is completed. The necessary sleep time is known because the RTS/CTS exchange includes the length of the messages to be exchanged.

B-MAC (B-media access control) [25] is another CSMA WSN MAC protocol that employs energy management in the small. B-MAC has a novel clear channel assessment (CCA) that minimizes false assessments as to whether the channel is busy or not. Obviously, if a radio listens and thinks the channel is free, but it is not, and it transmits, then it causes collisions. Hence, an accurate CCA improves energy savings. B-MAC also permits optional acknowledgements (ACKs), also saving energy. For example, due to sensing redundancy, it is not always necessary for every message to be received. On the other hand, important messages such as

new code downloads must receive ACKs. B-MAC permits turning on/off ACKs on a per-message basis. Another energy-saving feature of B-MAC is low-power listening. Here nodes sleep, periodically awake and listen. If a node has a message to send, it must transmit a preamble that indicates to those hearing it to stay awake for possible message exchange. If no preamble is heard, a node returns to sleep.

Specific problems such as long-preamble cost and burst message losses and specific features such a funnelling of messages as they near a base station are also addressed by many MAC protocols such as X-MAC (X-media access control) [40], Z-MAC (Zebra media access control) [41] and Funnelling MAC [42]. Here, again, energy management is paramount in these solutions.

(b) Routing

Modularity calls for routing protocols to focus on determining a route from a source node to a destination node (often a base station in WSNs). However, because of the minimal capacity of nodes and energy requirements, cross-cutting solutions that combine routing with support for query dissemination and data aggregation are common. Special needs for WSNs such as disseminating code or system parameters and communicating to all nodes in a region (called last mile communication) necessitate various forms of flooding. In most cases, supporting a high end-to-end packet reception ratio (PRR) at minimum energy expenditure is the main goal of the protocols. Minimizing delay or providing real-time guarantees are also sometimes requirements, but these metrics are not discussed here.

In wireless routing protocols such as DSR (dynamic source routing) [43] and AODV (ad-hoc on-demand distance vector) [44], end-to-end route discovery is used and the reverse path is used for responses and acknowledgements. However, route discovery is useful only if there are many subsequent messages, and reverse paths are useful if links are symmetric. In WSNs it is often unnecessary to first establish an end-to-end path, and many links are asymmetric.

Geographic forwarding (GF) is common in WSNs, and it treats each message independently and chooses the next hop that makes the most distance progress to the destination. It is an easy extension to GF to consider a combination of distance and remaining energy to choose the next hop. It is also an easy extension to consider neighbours with good PRR [29], otherwise, even though the distance to a given neighbour may be long, if the PRR is low, then it may require many attempts before a message is received, thereby wasting energy.

Directed diffusion [33] disseminates an interest (query) into the network to find nodes with the data of interest. It also permits data to be aggregated on the return trip. The aggregation minimizes the number of messages being sent and saves energy.

Flooding [45–47] is a very expensive (in messages and therefore energy consumed) communication scheme. Many optimizations are employed depending on the purpose of the flood. For example, last mile flooding enables communicating to all nodes within a range of a geographical coordinate, but is only instantiated in the area of the destination, saving messages. Nodes often keep message source and sequence number to prevent forwarding duplicates and to prevent looping. In other cases, a WSN may create a spanning tree and use that tree to flood.

(c) Localization

Node localization is a process where a node's geographic position is determined. Applications must know where an event occurs and routing protocols based on GF also use node locations. Even though localization for many WSNs may occur only once at system initialization time, it is necessary to minimize the number of messages involved, as too many messages would consume a significant amount of energy. Mobile WSNs—or if nodes are moved—necessitate re-running localization, thereby repeating the energy cost overheads.

A simple outdoor solution is to equip every node with a global positioning system (GPS). However, the cost, form factor and energy requirements often make this impracticable. Even with GPS, various nodes in the system may fail to acquire a GPS signal due to trees, tall buildings or other obstacles. Hence, even with using GPS, some additional protocol support is often required.

Many localization protocols use beacons from GPS-enabled nodes called anchors. If only 1–2% of the nodes have GPS, the costs are often manageable. However, the beacon nodes usually require more energy. In some systems, beacons communicate much further than other nodes in the system, requiring significantly more energy for the beacon nodes. In other systems, beacons communicate only in their neighbourhood. In all cases, solutions that minimize the required number of messages are preferred. For example, APIT (a point in triangle) [48] keeps the number of messages required very low, but does require beacons to have additional energy and to transmit over large distances when compared with non-beacon nodes.

Localization designs normally fall into one of two categories: range-based and range-free. The former requires special hardware for distance (range) or angle estimates, suffering high cost. The latter uses only connectivity information, suffering large estimation errors in localization. Specifically range-based solutions for localization such as time difference of arrival (TDOA) [49] require two transmitted signals per node. Other range-based schemes use a received signal strength indicator (RSSI) to estimate distance. This requires the use of multiple messages to average signal strength and then relate that signal strength to a distance estimate. Energy requirements for these approaches can be fairly low, but for TDOA additional hardware is needed, and RSSI-based solutions tend to be inaccurate.

Range-free solutions such as DV-Hop [50] and other enhanced versions [51] are robust in terms of their ability to localize all the nodes, but require a large number of messages, potentially severely impacting the energy consumption of a node.

(d) Time synchronization

Since WSNs are spatial–temporal systems, time synchronization is often critical for identifying when an event has occurred. This supports application functionality. In addition, various system-level protocols also depend on clock synchronization, such as many MAC, localization and other protocols.

In general, clocks on the individual nodes of a WSN drift and must be resynchronized periodically. The rate of drift depends on the physical properties of the clock, and the resynchronization period depends on the accuracy requirements

of the protocols using the clock as well as the need to minimize energy consumption caused by running the clock-synchronization protocol. The main cost is the number of messages that must be exchanged across the WSN.

The first consideration is the basic cost of the protocol. For example, NTP (network time protocol) is the clock-synchronization protocol used on the Internet. In addition to requiring significant space for code and data, it runs continuously in the background and transmits many messages to multiple time servers. The energy requirements for such a protocol are too high for WSNs. In TPSN (time-synchronization protocol for sensor networks) [52], a clock-synchronization protocol for WSNs, a spanning tree is built and then each pair of nodes exchanges two messages to perform clock synchronization. This overall cost is repeated at every clock resynchronization period.

The second consideration is to minimize the resynchronization events. Resynchronization should occur only when the clocks would no longer be accurate enough for their intended uses. Some solutions compute such a rate and simply run clock synchronization at that rate. To enable the rate of resynchronization to be reduced, it is also possible to estimate clock drift and then compensate for clock drift. This tends to extend the period before resynchronization needs to be re-run, thereby reducing energy requirements. This is achieved by on-demand synchronization (ODS) methods [53].

The third consideration is to schedule hardware clocks. Since a high-frequency always-on clock introduces excessive energy consumption, Schmid *et al.* [54] replace a high-resolution clock with a lower-frequency, temperature-compensated one through duty cycling, leading to a 10× reduction in power consumption.

4. Energy management in the large

Many WSNs add energy management techniques/protocols whose main purpose is to save energy. We call this energy management in the large. In this section, because of space limitations, we choose to present one system, called VigilNet [39,55,56], as a case study to explain the most common techniques to achieve collaborative energy savings in the large. VigilNet is a major effort to support long-term military surveillance, using large-scale micro-sensor networks. Besides requirements of accurate target tracking and classification, one of the key design goals of VigilNet is to achieve long-term surveillance in a realistic mission deployment. Owing to the small form factor and low-cost requirements, sensor devices such as the extreme scale nodes [57] are normally equipped with limited energy sources (e.g. two AA batteries). Moreover, because of the hostile environment and large number of nodes deployed, currently it is not operationally nor economically feasible to replace the energy source without introducing enormous effort and elements of risk to military personnel. In addition, the static nature of the nodes in the field prevents harvesting energy from ambient motion or vibration. The small form factor and possible lack of line of sight (e.g. deployment in forest) make it difficult to harvest solar energy. On the other hand, a three to six month system lifespan is essential to guarantee the effectiveness of normal military operations. Consequently, it is critical to investigate practical approaches to spending the energy budget effectively.

Unlike sensor systems that take samples according to predefined schedules, surveillance systems, such as VigilNet, are event-driven in nature. In such systems, operators are more interested in the data profile between inception and conclusion of the transient events. These systems should remain dormant in the absence of the events of interests, and switch to an active state when it is necessary to obtain high detection fidelity.

Normally, surveillance systems improve system lifetime through the following approaches.

- Coverage control: Surveillance systems are normally deployed with a high density (for instance, the default configuration of VigilNet [39,55] has 28 nodes per nominal radio range (30m)) for the sake of robustness in detection and fine-grained sensing during tracking. We can increase the system lifetime by activating only a subset of nodes at a given point of time, waiting for potential targets.
- Duty cycle scheduling: The duration of transient events within the area of surveillance, such as a target moving through the area, is normally non-negligible. Therefore, we can conserve energy without noticeably reducing the chance of detection by coordinating nodes' sleep schedules. Duty cycle scheduling is different from sample scheduling in the sense that duty cycle scheduling is at the micro-scale (milliseconds versus minutes) and it is strongly affected by the dynamics of the events (e.g. target velocity).
- Incremental activation: Sampling systems are normally designed for data logging. At each sample instance, all sensors should be activated to obtain a complete data profile. In contrast, surveillance systems are designed to detect transient events of interest. It is sufficient to activate only a subset of sensors for the initial detection. After the initial detection, we can activate other sensors to achieve a higher sensing fidelity and to perform classification.

In order to achieve long-term surveillance that meets the military requirement (e.g. three to six months), an aggressive 12–24-fold lifetime extension is essential, which indicates that a single energy management strategy is neither sufficient nor flexible. It is necessary to use a combination of different energy conservation techniques at different levels of the design.

- At the network level, we can divide the sensor field into multiple sections, called tripwire sections, and apply different working schedules to each tripwire section. A tripwire section can be in either an active or a dormant state, at a given point of time. When a tripwire section is dormant, all nodes within this section are put into a deep-sleep state to save energy. Surveillance in active tripwire sections can be done by either turning all nodes on or applying a section-level energy conservation technique as discussed below. The rationale behind the tripwire service is the existence of roads in the area of interest. By deploying the tripwire along the road, we can guarantee the detection of intruders without activating all sensors in the area. Similar designs can be found in the context of barrier

- coverage [58], where, instead of covering the whole region, it protects belt regions called barriers. Only nodes that form a barrier are awake to detect all movements that cut through the barrier.
- At the section level, we can select a subset of nodes, which we define as sentries, in charge of surveillance due to the high-density deployment. Sentry selection contains two phases. Nodes first exchange neighbouring information through hello messages. In each hello message, a sender attaches its node ID, position, number of neighbours and its own energy readings. After the first phase, each node builds up a one-hop neighbour table. In the second phase, each node sets a delay timer. The duration of the timer is calculated based on the weighted energy rank and weighted cover rank. The energy rank is assigned according to energy readings among neighbouring nodes (e.g. the node with the highest energy reading within a neighbourhood has a rank of 1). Similarly, the cover rank is assigned according to the number of neighbours within a node's sensing range. After the delay timer fires in one node, this node announces itself as a sentry by sending out a declaration message, while other nodes, in the vicinity of the declaring node, cancel their timers and become dormant non-sentry nodes. Rotation is periodically done among all nodes, selecting the nodes with more remaining energy as sentries. In addition to the aforementioned approach, we can apply other coverage algorithms to select sentries. For example, one can use off-duty eligibility rules [59] to turn nodes off as long as the neighbouring nodes can cover the area for them. We can also adopt a probing mechanism [60] to select sentries. In this mechanism, after a sleeping node wakes up, it broadcasts a probing message within a certain range and waits for a reply. If no reply is received within a time-out, it takes the responsibility of surveillance until it depletes its energy.
 - At the node level, we can apply a duty cycling technique to further save energy. Since a target can normally be sensed for a non-negligible period of time, it is not necessary to turn sentry nodes on all the time. We can schedule a sentry node in and out of sleep state to conserve energy. The sleep/awake schedule of a sentry node can be either independent of other nodes or coordinated with that of others in order to further reduce the detection delay and increase the detection probability.

One key research challenge for VigilNet and similar systems is to reconcile the need for network longevity with the need for fast and accurate target detection and classification. The former requires most sensor nodes to remain inactive, while the latter desires many active sensor nodes. We note that energy efficiency can be comparatively easy to achieve if events of interest are ubiquitously present. In sampling systems, data quality of some events, such as temperature and humidity, are not directly correlated with the responsiveness of the system. In contrast, responsiveness and awareness directly affect the performance of surveillance systems, which requires real-time tracking and classification.

In VigilNet, the balance between energy efficiency and performance is supported by the on-demand wake-up service. The on-demand control is stealthier compared with periodic control, because wake-up beacons are sent only when events occur. To support the on-demand control, we need to guarantee the

delivery of wake-up beacons. Because of the special stealthiness requirement, the non-sentries cannot synchronize their clocks with their sentries by exchanging messages. Therefore, neighbouring non-sentry nodes may no longer have a sleep/wake-up cycle synchronized with each other due to the clock drift, and a sentry cannot keep track of which of its neighbours are awake. To guarantee delivery, a non-sentry periodically wakes up and checks radio activity (detects preamble bytes) once per checking period (e.g. every second). If no radio activity is detected, this node goes back to sleep, otherwise it remains active for a period of time, preparing for incoming targets. If a sentry node wants to wake up all the neighbouring nodes, it only needs to send out a message with a long preamble with a length equal to or longer than the checking period of non-sentry nodes. Since in the rare-event model, the wake-up operations are done very infrequently, the long preamble does not introduce much energy consumption in sentry nodes. On the other hand, since the amount of time taken to check the radio activity is constant for specific radio hardware, the length of the checking period determines the energy consumption in non-sentry nodes. In general, a long checking period leads to lower energy consumption. However, to ensure that a sentry node wakes up the neighbouring non-sentry nodes before a target moves out of their sensing range, the checking period cannot be arbitrarily long. Theoretically, the upper bound of the checking period is $\sqrt{R^2 - r^2}/S$, where R is the radio range, r is the sensing range of the sentries and S is the speed of the target. Owing to other delays, such as sensor warm-up time, the checking period should be smaller than this theoretical bound.

From the case study of the VigilNet energy management subsystem, we have a few key observations. First, energy management is a cross-cutting issue that must be addressed at the different layers of a system design. Second, a single solution can only provide limited energy saving, and therefore it is often necessary to have a combination of different technologies. Third, energy management strikes a delicate balance between efficiency and performance. To effectively achieve the balance, it is necessary to maximize energy savings when a network is in idle mode and activate the network promptly when events of interest appear.

5. Summary

Energy management is and will continue to be a critical issue for WSNs. Even as low-power circuits and energy harvesting improve, there is a need to conserve energy so that such sensor node devices can run for many years. As discussed, energy management is a cross-cutting issue that must be addressed within individual protocols (energy management in the small) as well as a central overarching theme (energy management in the large). To date, many solutions have been developed for battery-based WSN systems. Today, more and more solutions are being developed that involve hybrid systems (battery and harvesting) and battery-less systems. Note that, as WSNs become commonplace and people depend upon them more and more, increased techniques for reliability, safety and security protection will be required. Solutions to support these techniques also have energy management implications. Discussions on these topics are beyond the scope of this paper.

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