Energy-Aware Wireless Microsensor Networks

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Self-configuring wireless sensor networks can be invaluable in many civil and military applications for collecting, processing, and disseminating wide ranges of complex environmental data. Because of this, they have attracted considerable research attention in the last few years. The WINS [1] and SmartDust [2] projects, for instance, aim to integrate sensing, computing, and wireless communication capabilities into a small form factor to enable low-cost production of these tiny nodes in large numbers. Several other groups are investigating efficient hardware/software system architectures, signal processing algorithms, and network protocols for wireless sensor networks [3]-[5].

Sensor nodes are battery driven and hence operate on an extremely frugal energy budget. Further, they must have a lifetime on the order of months to years, since battery replacement is not an option for networks with thousands of physically embedded nodes. In some cases, these networks may be required to operate solely on energy scavenged from the environment through seismic, photovoltaic, or thermal conversion. This transforms energy consumption into the most important factor that determines sensor node lifetime.

Conventional low-power design techniques [6] and hardware architectures only provide point solutions which are insufficient for these highly energy-constrained systems. Energy optimization, in the case of sensor networks, is much more complex, since it involves not only reducing the energy consumption of a single sensor node but also maximizing the lifetime of an entire network. The network lifetime can be maximized

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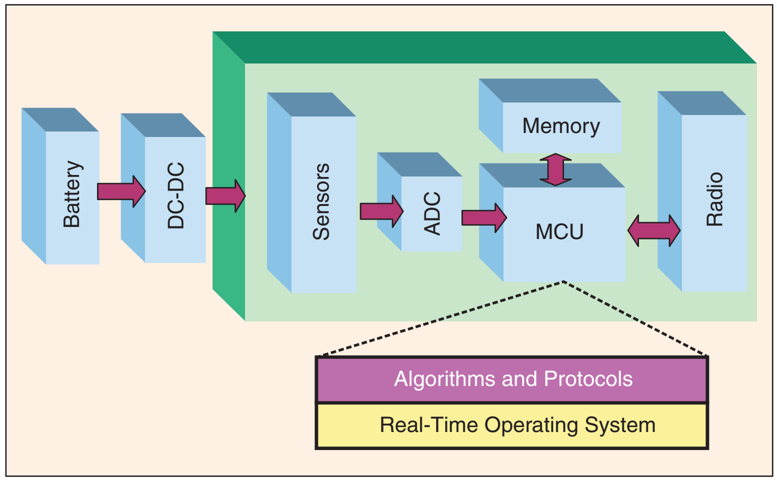
only by incorporating energy awareness into every stage of wireless sensor network design and operation, thus empowering the system with the ability to make dynamic tradeoffs between energy consumption, system performance, and operational fidelity. This new networking paradigm, with its extreme focus on energy efficiency, poses several system and network design challenges that need to be overcome to fully realize the potential of these wireless sensor systems.

A quite representative application in wireless sensor networks is event tracking, which has widespread use in applications such as security surveillance and wildlife habitat monitoring. Tracking involves a significant amount of collaboration between individual sensors to perform complex signal processing algorithms such as Kalman filtering, Bayesian data fusion, and coherent beamforming. This collaborative signal processing nature of sensor networks offers significant opportunities for energy management. For example, just the decision of whether to do the collaborative signal processing at the user end-point or somewhere inside the network has significant implication on energy and lifetime. We will use tracking as the application driver to illustrate many of the techniques presented in this article.



▲ 1. System architecture of a typical wireless sensor node.

Overview

This article describes architectural and algorithmic approaches that designers can use to enhance the energy awareness of wireless sensor networks. The article starts off with an analysis of the power consumption characteristics of typical sensor node architectures and identifies the various factors that affect system lifetime. We then present a suite of techniques that perform aggressive energy optimization while targeting all stages of sensor network design, from individual nodes to the entire network. Maximizing network lifetime requires the use of a well-structured design methodology, which enables energy-aware design and operation of all aspects of the sensor network, from the underlying hardware platform to the application software and network protocols. Adopting such a holistic approach ensures that energy awareness is incorporated not only into individual sensor nodes but also into groups of communicating nodes and the entire sensor network. By following an energy-aware design methodology based on techniques such as in this article, designers can enhance network lifetime by orders of magnitude.

Where Does the Power Go?

The first step in designing energy-aware sensor systems involves analyzing the power dissipation characteristics of a wireless sensor node. Systematic power analysis of a sensor node is extremely important to identify power bottlenecks in the system, which can then be the target of aggressive optimization. We analyze two popular sensor nodes from a power consumption perspective and discuss how decisions taken during node design can significantly impact the system energy consumption.

The system architecture of a canonical wireless sensor node is shown in Fig. 1. The node is comprised of four subsystems: i) a computing subsystem consisting of a microprocessor or microcontroller, ii) a communication subsystem consisting of a short range radio for wireless communication, iii) a sensing subsystem that links the node to the physical world and consists of a group of sensors and actuators, and iv) a power supply subsystem, which houses the battery and the dc-dc converter, and powers the rest of the node. The sensor node shown in Fig. 1 is representative of commonly used node architectures such as [1] and [2].

Microcontroller Unit

Providing intelligence to the sensor node, the microcontroller unit (MCU) is responsible for control of the sensors and the execution of communication protocols and signal processing algorithms on the gathered sensor data. Commonly used MCUs are Intel's StrongARM microprocessor and Atmel's AVR microcontroller. The power-performance characteristics of MCUs have been studied extensively, and several techniques have been proposed to estimate the power consumption of these embedded processors [7], [8]. While the choice of MCU is dictated by the required performance levels, it can also significantly impact the node's power dissipation characteristics. For example, the StrongARM microprocessor from Intel, used in high-end sensor nodes, consumes around 400 mW of power while executing instructions, whereas the ATmega103L AVR microcontroller from Atmel consumes only around 16.5 mW, but provides much lower performance. Thus, the choice of MCU should be dictated by the application scenario, to achieve a close match between the performance level offered by

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the MCU and that demanded by the application. Further, MCUs usually support various operating modes, including Active, Idle, and Sleep modes, for power management purposes. Each mode is characterized by a different amount of power consumption. For example, the StrongARM consumes 50 mW of power in the Idle mode, and just 0.16 mW in the Sleep mode. However, transitioning between operating modes involves a power and latency overhead. Thus, the power consumption levels of the various modes, the transition costs, and the amount of time spent by the MCU in each mode all have a significant bearing on the total energy consumption (battery lifetime) of the sensor node.

Radio

The sensor node's radio enables wireless communication with neighboring nodes and the outside world. Several factors affect the power consumption characteristics of a radio, including the type of modulation scheme used, data rate, transmit power (determined by the transmission distance), and the operational duty cycle. In general, radios can operate in four distinct modes of operation: Transmit, Receive, Idle, and Sleep. An important observation in the case of most radios is that operating in Idle mode results in significantly high power consumption, almost equal to the power consumed in the Receive mode [11]. Thus, it is important to completely shut down the radio rather than transitioning to Idle mode when it is not transmitting or receiving data. Another influencing factor is that as the radio's operating mode changes, the transient activity in the radio electronics causes a significant amount of power dissipation. For example, when the radio switches from sleep mode to transmit mode to send a packet, a significant amount of power is consumed for starting up the transmitter itself [9].

Sensors

Sensor transducers translate physical phenomena to electrical signals and can be classified as either analog or digital devices depending on the type of output they produce. There exists a diversity of sensors that measure environmental parameters such as temperature, light intensity, sound, magnetic fields, image, etc. There are several sources of power consumption in a sensor, including i) signal sampling and conversion of physical signals to electrical ones, ii) signal conditioning, and iii) analog-to-digital conversion. Given the diversity of sensors, there is no typical power consumption number. In general, however, passive sensors such as temperature, seismic, etc., consume negligible power relative to other components of sensor node. However, active sensors such as sonar rangers, array sensors such as imagers, and narrow field-of-view sensors that require repositioning such as cameras with pan-zoom-tilt can be large consumers of power.

Power Analysis of Sensor Nodes

Table 1 shows the power consumption characteristics of Rockwell's WINS node [10], which represents a high-end sensor node and is equipped with a powerful StrongARM SA-1100 processor from Intel, a radio module from Conexant Systems, and several sensors including acoustic and seismic ones. Table 2 gives the characteristics of the MEDUSA-II, an experimental sensor node developed at the Networked and Embedded Systems Lab, UCLA. The MEDUSA node, designed to be ultra-low power, is a low-end sensor node similar to the COTS Motes developed as part of the SmartDust project [2]. It is equipped with an AVR microcontroller from ATMEL, a low-end RFM radio module, and a few sensors. As can be seen from the tables, the power dissipation characteris-

Table 1. Power Analysis of Rockwell's Wins Nodes.

MCU Mode	Sensor Mode	Radio Mode	Power (mW)
Active	On	Tx (Power: 36.3 mW)	1080.5
		Tx (Power: 19.1 mW)	986.0
		Tx (Power: 13.8 mW)	942.6
		Tx (Power: 3.47 mW)	815.5
		Tx (Power: 2.51 mW)	807.5
		Tx (Power: 0.96 mW)	787.5
		Tx (Power: 0.30 mW)	773.9
		Tx (Power: 0.12 mW)	771.1
Active	On	Rx	751.6
Active	On	Idle	727.5
Active	On	Sleep	416.3
Active	On	Removed	383.3
Sleep	On	Removed	64.0
Active	Removed	Removed	360.0

tics of the two nodes differ significantly. There are several inferences that can be drawn from these tables:

- Using low-power components and trading off unnecessary performance for power savings during node design can have a significant impact, up to a few orders of magnitude.
- The node power consumption is strongly dependent on the operating modes of the components. For example, as Table 1 shows, the WINS node consumes only around one-sixth the power when the MCU is in Sleep mode, than when it is in Active mode.
- Due to extremely small transmission distances, the power consumed while receiving data can often be greater than the power consumed while transmitting packets, as is evident from Fig. 2. Thus, conventional network protocols, which usually assume the receive power to be negligible, are no longer efficient for sensor networks, and customized protocols which explicitly account for receive power have to be developed instead.
- The power consumed by the node with the radio in Idle mode is approximately the same with the radio in Receive mode. Thus, operating the radio in Idle mode does not provide any advantage in terms of power. Previously proposed network protocols have often ignored this fact, leading to fallacious savings in power consumption, as pointed out in [11]. Therefore, the radio should be completely shut off whenever possible to obtain energy savings.

Power management of radios is extremely important since wireless communication is a major power consumer during system operation.

Battery Issues

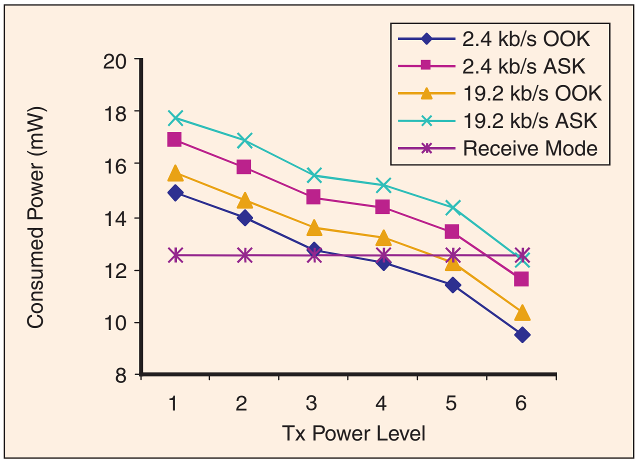
The battery supplies power to the complete sensor node and hence plays a vital role in determining sensor node lifetime. Batteries are complex devices whose operation depends on many factors including battery dimensions, type of electrode material used, and diffusion rate of the active materials in the electrolyte. In addition, there can be several nonidealities that can creep in during battery operation, which adversely affect system lifetime. We describe the various battery nonidealities and discuss system level design approaches that can be used to prolong battery lifetime.

Rated Capacity Effect

The most important factor that affects battery lifetime is the discharge rate or the amount of current drawn from

Table 2. Power Analysis of Medusa II Nodes.

MCU Mode	Sensor Mode	Radio Mode	Mod. Scheme	Data Rate	Power (mW)
Active	On	Tx(Power: 0.7368 mW)	OOK	2.4 kb/s	24.58
		Tx(Power: 0.0979 mW)	OOK	2.4 kb/s	19.24
		Tx(Power: 0.7368 mW)	OOK	19.2 kb/s	25.37
		Tx(Power: 0.0979 mW)	OOK	19.2 kb/s	20.05
		Tx(Power: 0.7368 mW)	ASK	2.4 kb/s	26.55
		Tx(Power: 0.0979 mW)	ASK	2.4 kb/s	21.26
		Tx(Power: 0.7368 mW)	ASK	19.2 kb/s	27.46
		Tx(Power: 0.0979 mW)	ASK	19.2 kb/s	22.06
Active	On	Rx	Any	Any	22.20
Active	On	Idle	Any	Any	22.06
Active	On	Off	Any	Any	9.72
Idle	On	Off	Any	Any	5.92
Sleep	Off	Off	Any	Any	0.02



2. *Power consumption of an RFM radio in various modes of operation.*

the battery. Every battery has a rated current capacity, specified by the manufacturer. Drawing higher current than the rated value leads to a significant reduction in battery life. This is because, if a high current is drawn from the battery, the rate at which active ingredients diffuse through the electrolyte falls behind the rate at which they are consumed at the electrodes. If the high discharge rate is maintained for a long time, the electrodes run out of active materials, resulting in battery death even though active ingredients are still present in the electrolyte. Hence, to avoid battery life degradation, the amount of current drawn from the battery should be kept under tight check. Unfortunately, depending on the battery type (lithium ion, NiMH, NiCd, alkaline, etc.), the minimum required current consumption of sensor nodes often exceeds the rated current capacity, leading to suboptimal battery lifetime.

Relaxation Effect

The effect of high discharge rates can be mitigated to a certain extent through battery relaxation. If the discharge current from the battery is cut off or reduced, the diffusion and transport rate of active materials catches up with the depletion caused by the discharge. This phenomenon is called the relaxation effect and enables the battery to recover a portion of its lost capacity. Battery lifetime can be significantly increased if the system is operated such that the current drawn from the battery is frequently reduced to very low values or is completely shut off [12].

DC-DC Converter

The dc-dc converter is responsible for providing a constant supply voltage to the rest of the sensor node while utilizing the complete capacity of the battery. The efficiency factor associated with the converter plays a big role in determining battery lifetime [13]. A low efficiency factor leads to significant energy loss in the converter, reducing the amount of energy available to other sensor node components. Also, the voltage level across the battery terminals constantly decreases as it gets discharged. The converter therefore draws increasing amounts of current from the battery to maintain a constant supply voltage to the sensor node. As a result, the current drawn from the battery becomes progressively higher than the current that actually gets supplied to the rest of the sensor node. This leads to depletion in battery life due to the rated capacity effect, as explained earlier. Fig. 3 shows the difference in current drawn from the battery and the current delivered to the sensor node for a lithium-ion coin cell battery.

Node Level Energy Optimization

Having studied the power dissipation characteristics of wireless sensor nodes, we now focus our attention to the issue of minimizing the power consumed by these nodes. As a first step towards incorporating energy awareness into the network, it is necessary to develop hardware/software design methodologies and system architectures that enable energy-aware design and operation of individual sensor nodes in the network.

Power-Aware Computing

Advances in low-power circuit and system design [6] have resulted in the development of several ultra-low-power microprocessors and microcontrollers. In addition to using low-power hardware components during sensor node design, operating the various system resources in a power-aware manner through the use of dynamic power management (DPM) [14] can reduce energy consumption further, increasing battery lifetime. A commonly used power management scheme is based on idle component shutdown, in which the sensor node (or parts of it) is shut down or sent into one of several low-power states if no interesting events occur. Such event-driven power management is extremely crucial in maximizing node lifetime. The core issue in shutdown-based DPM is deciding the state transition policy [14], since different states are characterized by different amounts of power consumption and state transitions have a nonnegligible power and time overhead.

While shutdown techniques save energy by turning off idle components, additional energy savings are possible in active state through the use of dynamic voltage scaling (DVS) [15]. Most microprocessor-based systems have a time-varying computational load, and hence peak system performance is not always required. DVS exploits this fact by dynamically adapting the processor's supply voltage and operating frequency to just meet the instantaneous processing requirement, thus trading off unutilized performance for energy savings. DVS-based power management, when applicable, has been shown to have significantly higher energy efficiency compared to shutdown-based power management due to the convex nature of the energy-speed curve [15]. Several modern processors such as Intel's StrongARM and Transmeta's Crusoe support scaling of voltage and frequency, thus providing control knobs for energy-performance management.

For example, consider the target-tracking application discussed earlier. The duration of node shutdown can be used as a control knob to trade off tracking fidelity against energy. A low operational duty cycle for a node reduces energy consumption at the cost of a few missed detections. Further, the target update rate varies, depending on the quality of service requirements of the user. A low update rate implies more available latency to process each sensor data sample, which can be exploited to reduce energy through the use of DVS.

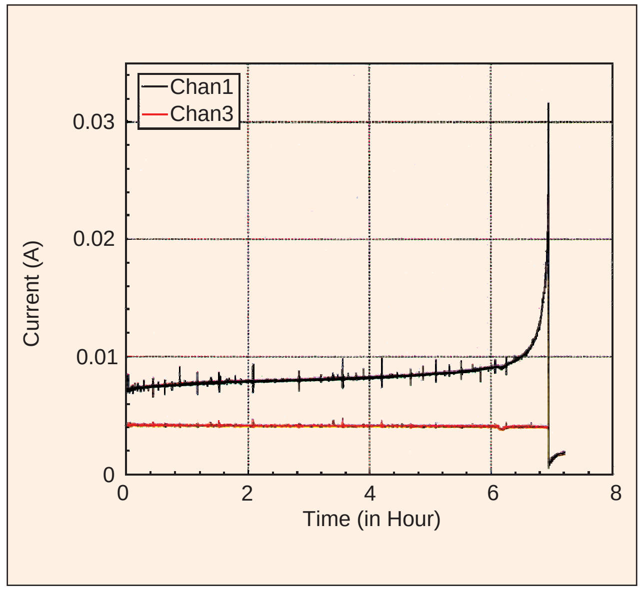
Energy-Aware Software

Despite the higher energy efficiency of application specific hardware platforms, the advantage of flexibility offered by microprocessor and DSP-based systems has resulted in the increasing use of programmable solutions during system design. Sensor network lifetime can be significantly enhanced if the system software, including the operating system (OS), application layer, and network protocols, are all designed to be energy aware.

The OS is ideally poised to implement shutdown-based and DVS-based power management policies, since it has global knowledge of the performance and fidelity requirements of all the applications and can directly control the underlying hardware resources, fine tuning the available performance-energy control knobs. At the core of the OS is a task scheduler, which is responsible for scheduling a given set of tasks to run on the system while ensuring that timing constraints are satisfied. System lifetime can be increased considerably by incorporating energy awareness into the task scheduling process [16], [17].

The energy-aware real-time scheduling algorithm proposed in [16] exploits two observations about the operating scenario of wireless systems to provide an adaptive power versus fidelity tradeoff. The first observation is that these systems are inherently designed to operate resiliently in the presence of varying fidelity in the form of data losses and errors over wireless links. This ability to adapt to changing fidelity is used to trade off against energy. Second, these systems exhibit significant correlated variations in computation and communication processing load due to underlying time-varying physical phenomena. This observation is exploited to proactively manage energy resources by predicting processing requirements. The voltage is set according to predicted computation requirements of individual task instances, and adaptive feedback control is used to keep the system fidelity (timing violations) within specifications.

The energy-fidelity tradeoff can be exploited further by designing the application layer to be energy scalable. This can be achieved by transforming application software such that the most significant computations are performed first. Thus, terminating the algorithm prematurely due to energy constraints does not impact



▲ *3. Current drawn form the battery (Chan1) and current supplied to the node (Chan3).*

the result severely. For example, the target tracking application described earlier involves the extensive use of signal filtering algorithms such as Kalman filtering. Transforming the filtering algorithms to be energy scalable trades off computational precision (and hence, tracking precision) for energy consumption. Several transforms to enhance the energy scalability of DSP algorithms are presented in [18].

Power Management of Radios

While power management of embedded processors has been studied extensively, incorporating power awareness into radio subsystems has remained relatively unexplored. Power management of radios is extremely important since wireless communication is a major power consumer during system operation. One way of characterizing the importance of this problem is in terms of the ratio of the energy spent in sending one bit of information to the energy spent in executing one instruction. While it is not quite fair to compare this ratio across nodes without normalizing for transmission range, bit error probability, and the complexity of instruction (8 bit versus 32 bit), this ratio is nevertheless useful. Example values for this ratio are from 1500 to 2700 for Rockwell's WIN nodes, 220 to 2900 for the MEDUSA II nodes, and around 1400 for the WINS NG 2.0 nodes from the Sensoria Corporation that are used by many researchers.

The power consumed by a radio has two main components to it: 1) an RF component that depends on the transmission distance and modulation parameters and 2) an electronics component that accounts for the power consumed by the circuitry that performs frequency synthesis, filtering, up-converting, etc. Radio power management is a nontrivial problem, particularly since the well-understood techniques of processor power management may not be directly applicable. For example,

In addition to sensing and communicating its own data to other nodes, a sensor node also acts as a router, forwarding packets meant for other nodes.

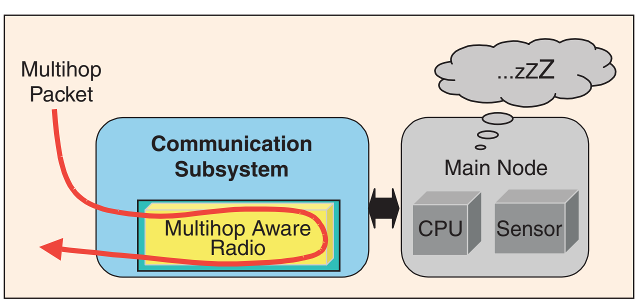
techniques such as dynamic voltage and frequency scaling reduce processor energy consumption at the cost of an increase in the latency of computation. In the case of radios, however, the electronics power can be comparable to the RF component (which varies with the transmission distance). Therefore, slowing down the radio may actually lead to an increase in energy consumption. Other architecture specific overheads like the startup cost of the radio can be quite significant [9], making power management of radios a complex problem. The various tradeoffs involved in incorporating energy awareness into wireless communication will be discussed further in the next section.

Energy-Aware Packet Forwarding

In addition to sensing and communicating its own data to other nodes, a sensor node also acts as a router, forwarding packets meant for other nodes. In fact, for typical sensor network scenarios, a large portion (around 65%) of all packets received by a sensor node need to be forwarded to other destinations [19]. Typical sensor node architectures implement most of the protocol processing functionality on the main computing engine. Hence, every received packet, irrespective of its final destination, travels all the way to the computing subsystem and gets processed, resulting in a high energy overhead. The use of intelligent radio hardware, as shown in Fig. 4, enables packets that need to be forwarded to be identified and redirected from the communication subsystem itself, allowing the computing subsystem to remain in Sleep mode, saving energy [19].

Energy-Aware Wireless Communication

While power management of individual sensor nodes reduces energy consumption, it is important for the communication between nodes to be conducted in an energy efficient manner as well. Since the wireless transmission of data accounts for a major portion of the total energy consumption, power management decisions that take into account the effect of internode communication yield significantly higher energy savings. Further, incorporating power management into the communication process enables the diffusion of energy awareness from an individual sensor node to a group of communicating nodes, thereby enhancing the lifetime of entire regions of the network. To achieve power-aware communication it is necessary to identify and exploit the various performance-energy tradeoff knobs that exist in the communication subsystem.



▲ *4. Energy-aware packet forwarding architecture.*

Modulation Schemes

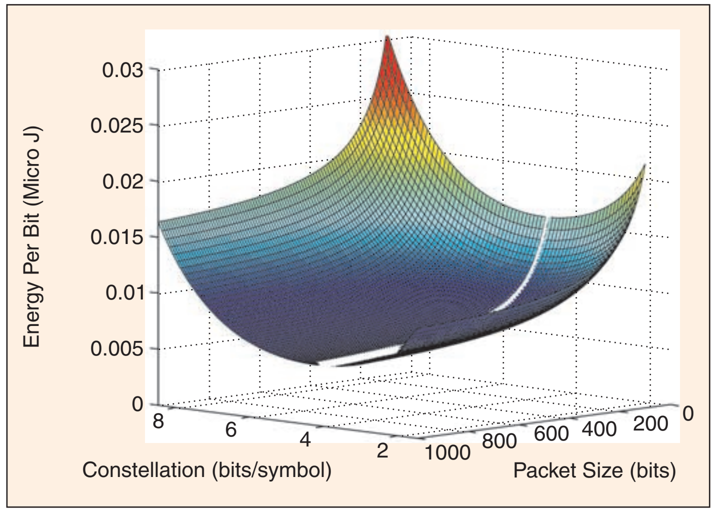
Besides the hardware architecture itself, the specific radio technology used in the wireless link between sensor nodes plays an important role in energy considerations. The choice of modulation scheme greatly influences the overall energy versus fidelity and latency tradeoff that is inherent to a wireless communication link. Equation (1) expresses the energy cost for transmitting one bit of information, as a function of the packet payload size L, the header size H, the fixed overhead E_{start} associated with the radio startup transient, and the symbol rate R_S for an M-ary modulation scheme [9], [20]. P_{elec} represents the power consumption of the electronic circuitry for frequency synthesis, filtering, modulating, upconverting, etc. The power delivered by the power amplifier, P_{RF}, needs to go up as M increases, to maintain the same error rate.

$$E_{\text{bit}} = \frac{E_{\text{start}}}{L} + \frac{P_{\text{elec}} + P_{\text{RF}}(M)}{R_S \times \log_2 M} \times \left(1 + \frac{H}{L}\right). \tag{1}$$

Fig. 5 plots the communication energy per bit as a function of the packet size and the modulation level M. This curve was obtained using the parameters given in Table 3, which are representative for sensor networks, and choosing quadrature amplitude modulation (QAM) [9], [20]. The markers in Fig. 5 indicate the optimal modulation setting for each packet size, which is independent of L. In fact, this optimal modulation level is relatively high, close to 16-QAM for the values specified in Table 3. Higher modulation levels might be unrealistic in low-end wireless systems, such as sensor nodes. In these scenarios, a practical guideline for saving energy is to transmit as fast as possible, at the optimal setting [9]. However, if for reasons of peak-throughput, higher modulation levels than the optimal one need to be provided, adaptively changing the modulation level can lower the overall energy consumption. When the instantaneous traffic load is lower than the peak value, transmissions can be slowed down, possibly all the way to the optimal operating point. This technique of dynamically adapting the modulation level to match the instantaneous traffic load, as part of the radio power management, is called modulation scaling [20]. It is worth noting that dynamic modulation scaling is the exact counterpart of dynamic voltage scaling, which has been shown to be extremely effective for processor power management, as described earlier.

The above conclusions are expected to hold for other implementations of sensor network transceivers as well. Furthermore, since the startup cost is significant in most radio architectures [9], it is beneficial to operate with as large a packet size as possible, since it amortizes this fixed overhead over more bits. However, aggregating more data into a single packet has the downside of increasing the overall latency of information exchange.

The discussion up until now has focused on the links between two sensor nodes, which are characterized by their short distance. However, when external users interact with the network, they often times do so via specialized gateway nodes [22], [23]. These gateway nodes offer long-haul communication services and are therefore in a different regime where P_{RF} dominates P_{elec}. In this case, the optimal M shifts to the lowest possible value, such that it becomes beneficial to transmit as slow as possible, subject to the traffic load. In this regime, modulation scaling is clearly very effective [20].



▲ *5. Radio energy per bit as a function of packet size and modulation level.*

Coordinated Power Management to Exploit Computation Communication Tradeoff

Sensor networks involve several node-level and network-wide computation-communication tradeoffs, which can be exploited for energy management. At the individual node level, power management techniques such as DVS and modulation scaling reduce the energy consumption at the cost of increased latency. Since both the computation and communication subsystems take from the total acceptable latency budget, exploiting the inherent synergy between them to perform coordinated power management will result in far lower energy consumption. For example, the relative split up of the available latency for the purposes of dynamic voltage scaling and dynamic modulation scaling significantly impacts the energy savings obtained. Fig. 6 shows a system power management module that is integrated into the OS and performs coordinated power management of the computing, communication and sensing subsystems.

The computation-communication tradeoff manifests itself in a powerful way due to the distributed nature of these sensor networks. The network's inherent capability for parallel processing offers further energy optimization potential. Distributing an algorithm's computation among multiple sensor nodes enables the computation to be performed in parallel. The increased allowable latency per computation enables the use of voltage scaling or other energy-latency tradeoff techniques. Distributed computing algorithms, however, demand more internode collaboration, thereby increasing the amount of communication that needs to take place.

These computation-communication tradeoffs extend beyond individual nodes to the network level, too. As we will discuss in the next section, the high redundancy present in the data gathering process enables the use of data-combining techniques to reduce the amount of data to be communicated, at the expense of extra computation at individual nodes to perform data aggregation.

Link Layer Optimizations

While exploring energy-performance-quality tradeoffs, reliability constraints also have to be considered, which are related to the interplay of communication packet losses and sensor data compression. Reliability decisions are usually taken at the link layer, which is responsible for some form of error detection and correction. Adaptive error correction schemes were proposed in [24] to reduce energy consumption, while maintaining the bit error rate (BER) specifications of the user. For a given BER requirement, error control schemes reduce the transmit power required to send a packet, at the cost of additional processing power at the transmitter and receiver. This is especially useful for long-distance transmissions to gateway nodes, which involve large transmit power. Link layer techniques also play an indirect role in reducing energy consumption. The use of a good error control scheme minimizes the number of times a packet retransmissions, thus reducing the power consumed at the transmitter as well as the receiver.

Network-Wide Energy Optimization

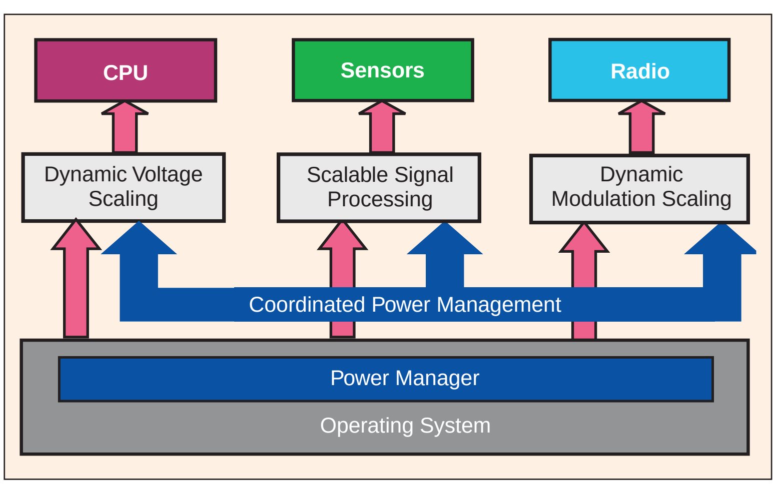
Incorporating energy awareness into individual nodes and pairs of communicating nodes alone does not solve the energy problem in sensor networks. The network as a whole should be energy aware, for which the network-level global decisions should be energy aware.

Table 3. Typical Radio Parameters for Sensor Networks.	
E_{start}	1 μJ
P_{elec}	12 mW
P_{RF}	1 mW for 4-QAM
R_S	1 Mbaud
H	16 bits

Traffic Distribution

At the highest level of the sensor network, the issue of how traffic is forwarded from the data source to the data sink arises. Data sinks typically are user nodes or specialized gateways that connect the sensor network to the outside world. One aspect of traffic forwarding is the choice of an energy efficient multihop route between source and destination. Several approaches have been proposed [3], [23], [25] which aim at selecting a path that minimizes the total energy consumption.

However, such a strategy does not always maximize the network lifetime [26]. Consider the target-tracking example again. While forwarding the gathered and processed data to the gateway, it is desirable to avoid routes through regions of the network that are running low on energy resources, thus preserving them for future, possibly critical detection and communication tasks. For the same reason, it is, in general, undesirable to continuously forward traffic via the same path, even though it minimizes the energy, up to the point where the nodes on that path are depleted of energy, and the network connectivity is compromised. It would, instead, be preferable to spread the load more uniformly over the network. This general guideline can increase the network lifetime in typical scenarios, although this is not always the case [26] as the optimal distribution of traffic load is possible only when future network activity is known.



▲ 6. Coordinated power management at the node level to exploit computation-communication tradeoffs.

Topology Management

The traffic distribution through appropriate routing essentially exploits the macroscale redundancy of possible routes between source and destination. On each route, however, there is also a microscale redundancy of nodes that are essentially equivalent for the multihop path. In typical deployment scenarios, a dense network is required to ensure adequate coverage of both the sensing and multihop routing functionality, in addition to improving network fault-tolerance [11], [27]. It is immediately apparent that there exist several adaptive energy-fidelity tradeoffs here too. For example, in target tracking, denser distributions of sensors lead to increasingly precise tracking results. However, if network lifetime is more critical than tracking precision, tracking could be done using data samples from fewer nodes. In addition to reducing the computational complexity itself, this also reduces the communication requirements of the nonparticipating nodes since they no longer have to send in their data to be processed.

Despite the inherent node redundancy, these high densities do not immediately result in an increased network lifetime, as the radio energy consumption in Idle mode does not differ much from that in Transmit or Receive mode. Only by transitioning the radio to the Sleep state can temporarily quiescent nodes conserve battery energy. In this state, however, nodes cannot be communicated with and have effectively retracted from the network, thereby changing the active topology. Thus, the crucial issue is to intelligently manage the sleep state transitions while providing robust undisturbed operation.

This reasoning is the foundation for the time slotted MAC protocol for sensor networks in [22] where the nodes only need to wake up during time slots that they are assigned to, although this comes at the cost of maintaining time synchronization. An alternative approach advocates explicit node wake up via a separate, but low-power, paging channel. In addition, true topology management explicitly leverages the fact that in high node density several nodes can be considered backups of each other with respect to traffic forwarding. The GAF protocol [11] identifies equivalent nodes based on their geographic location in a virtual grid such that they replace each other directly and transparently in the routing topology. In SPAN [27], a limited number of coordinator nodes are elected to forward the bulk of the traffic as a backbone within the ad-hoc network, while other nodes can frequently transition to a sleep state. Both GAF and SPAN are distributed protocols that provision for periodic rotation of node functionality to ensure fair energy consumption distribution. STEM [28] goes beyond GAF and SPAN in improving the network lifespan by exploiting the fact that most of the time the network is only sensing its environment waiting for an event to happen.

By eliminating GAF and SPAN's restriction of network capacity preservation at all times, STEM trades off an increased latency to set up a multihop path to achieve much higher energy savings.

Computation Communication Tradeoffs

Intelligent routing protocols and topology management ensure that the burden of forwarding traffic is distributed between nodes in an energy-efficient (i.e., network lifetime improving) fashion. Further enhancements are possible by reducing the size of the packets that are forwarded. As mentioned earlier, each node already processes its sensor data internally to this end. Consider the target tracking application. Due to high node densities, a target is detected not only by a single node, but also by an entire cloud of nearby nodes, leading to a high degree of redundancy in the gathered data. Combining the information from the nodes in this cloud via in-network processing can both improve the reliability of the detection event/data and greatly reduce the amount of traffic. One option is to combine the sensor readings of different nodes in a coherent fashion via beam-forming techniques [22]. Alternatively, noncoherent combining, also known as data fusion or aggregation, can be used, which does not require synchronization, but is less powerful. Several alternatives have been proposed to select the nodes that perform the actual combining, such as winner election [22], clustering [23], or traffic steered [26]. These techniques illustrate the effectiveness of exploiting network wide computation-communication tradeoffs.

Overhead Reduction

The sensor data packet payload can be quite compact due to in-network processing, with reported packet payloads as low as 8 to 16 bits [22]. Also, attribute-based naming and routing are being used [3], where the more common attributes can be coded in fewer bits. Short random identifiers have been proposed to replace unique identifiers for end-to-end functions such as fragmentation/reassembly. Spatial reuse, combined with Huffman-coded representation, can significantly reduce the size of MAC addresses compared to traditional network-wide unique identifiers [21]. Packet headers using attribute-based routing identifiers and encoded reusable MAC addresses are very compact, of the order of 10 bits. This reduction will become more important as radios with smaller startup cost are developed [9].

Conclusions

Sensor networks have emerged as a revolutionary technology for querying the physical world and hold promise in a wide variety of applications. However, the extremely energy constrained nature of these networks necessitate that their design and operation be done in an energy-aware manner, enabling the system to dynamically make tradeoffs between performance, fidelity, and energy consumption. We have presented several energy optimization and management techniques at node, link, and network level, leveraging which can lead to significant enhancement in sensor network lifetime.

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