Energy Conservation in Sensor Networks at the Link and Network Layers

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***Abstract*— This chapter surveys network-level approaches to conserve energy in sensor networks. We consider protocols for transmission power control, media access control, topology control, and energy-aware routing, surveying relevant literature and describing approaches that have been considered.**

***Index Terms*— sensor network, transmission power control, media access control, topology control, routing, energy conservation**

I. Introduction

Sensor networks promise to place sensors in the physical world to gather information, communicate, and act. All of these steps consume *energy*. With limited battery capacity, sensor networks are characterized by the situation where "each bit sent brings that node closer to death" [1]. Some sensor networks today add energy harvesting with solar panels or other more experimental methods, but even there careful use of energy is essential to an operational system.

Given a limited amount of energy or a limited recharge rate, *energy conservation* becomes a goal. A successful sensor network will minimize energy consumption at all levels of the system, from the application down to the hardware itself. This chapter considers *network-level* opportunities for energy conservation, with emphasis on the media-access control (MAC) level, topology control protocols, and routing-level issues.

II. Radio Transmission Power Control

We begin our survey of energy conservation by considering radio transmission power control. Transmission power is often integrated with the MAC protocol or routing protocol, or sometimes it is set external to the system.

Transmission power control is important for several reasons: first, adjusting power can be important to *guarantee connectivity*. Second, since transmission power indicates a radio's "footprint", controlling power is essential to *managing density* and encouraging spatial reuse of spectrum. Finally, minimizing transmission power can reduce energy consumption, both directly, by requiring less power to send, and indirectly, by reducing contention with other transmitting nodes.

Guaranteeing connectivity and managing density are related problems. By balancing connectivity and density wireless networks maximize *spatial reuse* of the spectrum. Power control is a key component to this process. There is a very, very large body of literature around analysis and protocol design for wireless power control. We describe only two examples of early work here. Ramanathan and Rosales-Hain demonstrated how to select transmission power to balance connectivity and energy consumed [2]. Many approach the subject from the MAC layer. A representative MAC protocol that considers power control is PCMA [3]. It focuses on optimizing spatial channel reuse, and extends an RTS/CTS mechanism to support variable power. They demonstrate about 50% better throughput when nodes and traffic are clustered and power control is enabled.

Efficient spatial use also affects the fundamental performance limits of the sensor network. For example, Gupta and Kumar's work establishes a theoretical bound on the capacity of a network indicating that wireless network capacity tracks $\Omega(\sqrt{n})$ as the number of nodes increase, assuming optimal transmission power and uniform distributions of sources and sinks [4]. Selection of optimal transmission power is necessary for their results.

Fewer researchers focus on power control to reduce energy consumption. The focus is most often on connectivity and spatial reuse because those are more pressing issues in systems design, particularly at longer ranges. The benefits of short-range transmission have been observed by Kaiser and Pottie, both due to the d^2 cost of longer-distance transmission, and because of the opportunity to trade local processing for transmission [5]. Radio transmission power can be a significant part of energy consumption at short ranges, but without care other component costs can dominate. For example, the CC1000 radio is widely used in sensor networks on platforms such as Mica2 Motes, and its output power ranges over a factor of 5 (from 5–27mA) [6]. However, the fixed cost of listening makes transmission power differences insignificant at low duty cycles. If 2% of time is spent transmitting, for example, the maximum energy savings is only 8%. Avoiding collisions by spatial reuse doubles the savings, by comparison, since after a collision both parties must retransmit.

Figure 1 illustrates these concepts by considering two transmission powers, r and R, where $R \approx 3r$. For communication from node a to d, two one can either transmit in one hop at full power (R), or in three hops a–b–c–d, each at reduced power of r. Using a simple d^2 energy model, the relative costs of these transmissions are $1 \times 3^2 = 9$ for one hop with R and $3 \times 1^2 = 3$ for three hops with r, demonstrating the possible energy conservation from shorter, multi-hop communication. This example also shows the possibility for spatial reuse and reduced contention enabled by lower-power transmission. With strength-r transmissions, concurrent communications are possible between nodes a–b and nodes d–e, while if node a

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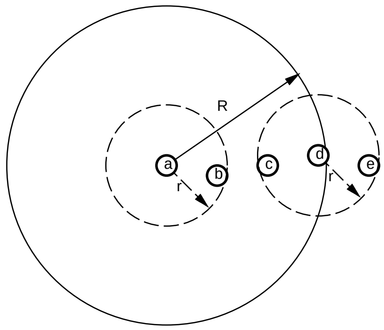


Fig. 1. Control of transmission power to promote spatial reuse and reduce energy requirements.

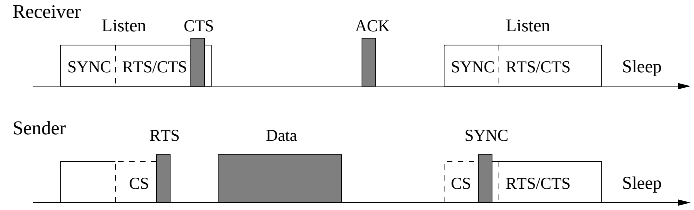


Fig. 2. Packet exchanges in S-MAC with listen/sleep cycles. CS stands for carrier sense.

communicates directly with node d at strength R, node d must be silent to avoid interference. Of course these examples are greatly simplified compared to the real world, where radio propagation is not spherical or symmetric, and listening and other costs must be considered (as described in the next section). However, it illustrates the principles of power control.

Figure shows the reduced contention and increased spatial reuse with short-range communications as a result of less interfering nodes.

When power control is considered for energy savings it is often viewed as part of the routing layer. An example protocol from this domain is LEACH [7]. Rather than sending data directly to a central site, nodes form clusters. Data is sent via a short hop to the cluster head, then via a long hop to the sink. By rotating cluster heads over time, energy consumption is reduced and distributed evenly, allowing a five-fold increase in network lifetime.

Systematic studies of the interactions between power control and routing protocols indicate the importance of considering interactions to ensure a reliable overall system [8].

III. Medium Access Control

We next consider energy conservation opportunities at the MAC level. For our purposes, we will assume that transmission power has been fixed. This leaves four areas of energy consumption that can be avoided: *collisions* consume energy by corrupting otherwise good packets. *Idle listening* is a major source of energy consumption when the radio is kept powered on for potential incoming transmissions. *Overhearing* transmitting packets consumes energy in a busy network when a node spends effort receiving packets destined to other nodes. Finally, *control packets* consume energy that is not directly sending useful data. A number of approaches have been proposed to reduce each of these costs: TDMA, and contention-based protocols with scheduled contention periods, asynchronous, paging channels, and low-power listening. We briefly describe each of these below.

Several MAC-level approaches have been proposed to reduce these costs. The first class is schedule-based protocols. *Time-division multiple-access* protocols can avoid collisions, idle listening, and overhearing by scheduling transmit and listen periods. TDMA protocols require strict time synchronization, often provided by infrastructure such as a base station. The infrastructure mode of IEEE-802.11 incorporates a contention-free interval, which adopts a TDMA-like structure coordinated by the access point [9], avoiding all three kinds of overhead. Bluetooth behaves similarly in a cluster, called *piconet*, where a master polls each slave for possible transmissions. Inter-cluster communication and interference are handled by CDMA. Sohrabi and Pottie have proposed a peer-to-peer transmission scheduling protocol for sensor networks [10]. Their approach avoids base-stations, but it depends on assigning different channels (CDMA or FDMA) to any interfering links to allow concurrent transmissions, and as a result has lower channel utilization.

Contention-based protocols are a second class of MAC protocols. They relax the tight synchronization requirements of TDMA protocols and use carrier-sense multiple access (CSMA) techniques to provide more flexibility in multi-hop communications and better robustness to topology changes. However, because these protocols contend to access the channel, collisions occur, and basic protocols in this class have costs for idle listening and overhearing. *IEEE-802.11 ad hoc mode* is a very widely used contention-based protocol. It uses carrier-sensing and randomized back-offs to reduce the likelihood of collisions [9]. To reduce idle listening, it defines a power save mode (PSM), allowing nodes to periodically enter sleep state. The PSM assumes a single-hop network and so time synchronization is easy. In multi-hop operation, it may have problems in clock synchronization, neighbor discovery and network partitioning [11].

Overhearing is another source of energy waste. PAMAS first observed the costs of overhearing and suggested using two channels, one for control traffic and the other for data traffic [12]. By keeping the data channel off when packets are exchanged between other nodes overhearing can be avoided.

Scheduled contention protocols are a subset of contention based protocols. Besides the PSM in 802.11 ad hoc mode, *S-MAC* is a second protocol in this class [13], [14]. In S-MAC each node adopts a listen/sleep cycle. Contention occurs only during a brief listen period, reducing the cost of idle listening. Figure 2 shows how two nodes exchange packets with the listen/sleep cycles. When there is no data, nodes enters the sleep mode after the brief listening. Otherwise, they use their sleep time to transmit data packets. During the data transmission, nodes other than the source and destinations sleep to avoid energy consumed due to overhearing (a generalization of PAMAS to in-channel signaling). S-MAC maintains a loose time synchronization between nodes to synchronize schedules, and it allows nodes to adopt multiple schedules, if necessary,

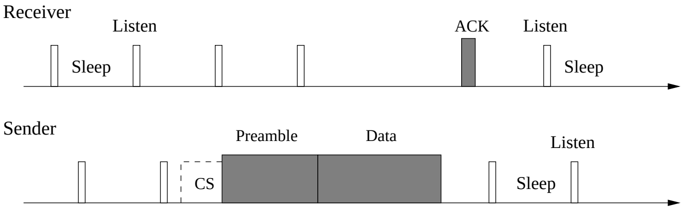
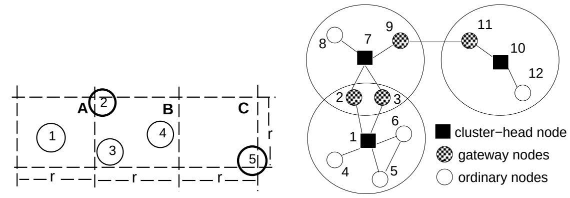


Fig. 3. Packet exchanges in low-power listening. CS stands for carrier sense.



(a) Geographical node equivalence

(b) Topological node equivalence

Fig. 4. Node equivalence in dense sensor networks (examples from [20]).

to support distributed, multi-hop operation. Recently adaptive listen [14] and T-MAC [15] have been proposed to improve multi-hop transmission with sleep-cycled MAC protocols.

Asynchronous schemes are a fourth class of MAC protocols. Tseng *et al.* [11] proposed asynchronous wake-up schemes to extend the 802.11 PS mode into multi-hop operations. Their basic idea is to design wake-up patterns that guarantee neighboring nodes have overlapping listen intervals no matter how large their clock differences are. Zheng *et at.* [16] proposed an optimal design of the asynchronous sleep patterns to minimize wake-up time by formulating the problem as the block design in combinatorics. Asynchronous wake-up schemes completely remove the requirement of time synchronizations. Its major drawback is the inefficiency in broadcasting, since all nodes wake up independently.

Paging channels are another approach to reduce energy consumption: the primary radio is left off when there is no traffic, and a secondary low-power radio (the paging channel) is used to wake up nodes when data needs to be sent. STEM [17] is an on-demand wake-up protocol using a second radio as a paging channel. In addition to using a low-power paging radio, STEM further reduces energy consumption by letting the paging radio periodically poll the medium for traffic. A sender needs to send a wake-up signal that is at least the length of the period. An advantage of using a second radio is the ability to completely avoid interference to the possible transmissions on the main radio.

This approach for *low-power listening* has been generalized to operate as the primary energy conservation mechanisms with a single radio [18], [19]. A sleeping node periodically wakes up and briefly polls the medium. It stays in active mode only when activity is detected. A sender wakes up a receiver by sending packets with a preamble that is as long as the polling period. Figure 3 shows the packet exchanges in low power listening. The benefit of low-power listen is that very brief polling is possible, as little as 3ms on Mica2 motes [18], with most of the delay being time for the radio's crystal to stabilize. The disadvantage is that transmitting nodes must precede packets with extremely long preambles. It increases control overhead and reduces channel utilization, especially when traffic is heavy. On-demand wake-up offers the most aggressive reduction in listen time. For very low duty cycle networks (less than a few percent) and light traffic it appears quite attractive.

In summary, schedule-based MAC protocols, such as TDMA, avoid collisions, and are easy to reduce idle listening and overhearing. However they can be a poor match to multi-hop networks because of uneven energy usage due to clustering and the need for strict time synchronization. Contention protocols do not have these disadvantages, but basic protocols consume energy in collisions, idle listening and overhearing. Versions of contention protocols reduce each of these costs, with four techniques to reduce idle listening: scheduled contention periods, asynchronous, paging channels, and low-power listening, each with its own advantages and disadvantages.

IV. Topology Control Protocols: Between MAC and Routing

Although MAC protocols may put the radio to sleep, they provide the illusion of continuous connectivity to all nodes, buffering and delaying transmission of packets if necessary. *Topology control protocols* are a class of protocols that set between the MAC layer and routing that violate this abstraction by turning nodes off for longer periods of time. Topology control protocols turn off as many nodes as possible to conserve energy, aiming to leave only enough on to keep a connected topology. This constraint assures that data can transit the network, and that any node that attempts to send data can connect to the network. However, since some nodes are off, these nodes cannot be destinations for data.

Topology control protocols complement MAC-level sleep/wakeup protocols for two reasons. First, they typically operate at much coarser timescales, cycling radios on the order of minutes rather than seconds. Coarser granularity reduces mode-switch costs and allows clocks to be less closely synchronized. Second, by relaxing the assumption that all nodes are reachable, sleeping nodes have no need to poll for traffic.

The main disadvantage of topology control protocols is that "edge" nodes will be sleeping and unreachable for long periods of time. If individual nodes are considered important or explicitly addressed, this constraint may be a problem, requiring backbone or source nodes to cache and resend data. On the other hand, in a data-centric sensor network where queries are made for classes of data rather than specific end-nodes, this restriction will likely have little impact. For example, the query "seismic sensors covering region X" can be satisfied by whatever sensors are currently awake.

We briefly consider two classes of of topology control protocols: geographic-based protocols, exemplified by GAF [21], and topology-based protocols such as SPAN [22]. Both aim to construct a connected "backbone" network; they differ in how to select nodes to form that network.

Geographic-based protocols such as GAF use physical location to infer network coverage [21]. Given a nominal radio range, nodes impose a logical grid over the network such that a node in any grid cell is guaranteed to be able to reach any node in any neighboring grid. One node in each grid is then elected to remain on to guarantee a connected network, while other nodes sleep to conserve energy. Figure 4(a) shows an example virtual grid where r is the nominal radio range and one of nodes 2, 3, and 4 needs to remain awake. Geographic topology control protocols can be fairly simple, but they require a source of node location and they depend on lower-bound estimate of radio range.

By contrast, topology-based protocols directly measure network connectivity, electing *coordinators* to guarantee coverage. In Span [22], a node becomes a coordinator if any of its neighbors cannot reach each other directly or via one or two coordinator nodes. This election algorithm requires that all nodes share their neighbor information with each other, and it measures local connectivity directly by this information. Figure 4(b) shows a sample cluster topology where black nodes (1, 7, and 10) are cluster heads, gray nodes form gateways between clusters (9, 11, and either 2 or 3), and the remainder are edge nodes. Backbone election can also preferentially select nodes with wall-power, as proposed in ReOrg [23] or traffic and congestion [24].

Performance of topology protocols is affected by network density and node mobility. Energy savings and network lifetime are proportional to density. If density is defined as the mean number of neighbors each node has, a basic network requires a density of 6–10 to be connected if all nodes are awake. Topology protocols have been evaluated at densities of 20–100 neighbors. Densities of 20–40 exhibit network lifetimes of 3–4 times a comparable network without topology control, both with GAF and Span. While one would expect lifetime to increase linearly with density, simulation results for the protocols suggest efficiency decreases at higher densities due to overheads of electing and switching backbone nodes.

Although many sensor networks are static, topology control protocols have been evaluated with mobile nodes. Since topology control protocols select a minimum backbone of nodes, all are important to maintain connectivity. This balance can easily be disrupted by mobility. Both GAF and Span probe more frequently to cope with mobility, thus reducing their efficiency. Since GAF presumes nodes know their location it can use predicted movement to predict when backbone nodes must be reselected; CEC adds this capability to a Span-like protocol [20].

Topology control protocols can interact or be independent of MAC and routing protocols. GAF and CEC are independent of each, but problems can occur if topology control puts a node on a route to sleep [20]. These problems can be avoided by a fast-repairing routing layer or by explicit signaling between topology control and other layers. STEM is an example of topology control integrated with a paging-channel-based MAC protocol [25], using analysis to suggest MAC-level energy conservation can add a 10-fold savings over GAF-alone. Other researchers have explored integration of topology control with transmission power control [26].

V. ROUTING

Routing is the highest protocol layer we review in this chapter. Since routing protocol defines the interactions between many nodes as data travels in a multi-hop network, it is not surprising that there are several different goals that routing may optimize. Singh *et al.* describe five possible goals [27]; we summarize four here: minimizing total energy consumed, maximizing time until network partition, and minimizing variance in energy at each node, or minimizing the "cost" per packet. Directly minimizing energy consumed can be at odds with the middle two goals since the minimum-energy path may concentrate traffic on certain nodes, unevenly draining their batteries. The final goal seeks to balance these trade-offs, defining "cost" as a function of remaining battery lifetime. However, the paper reports that optimizing the cost is NP-complete. (Chang and Tassiulas formulated energy-aware routing as a linear programming problem, allowing polynomial solutions [28].)

Traditional routing algorithms such as Bellman-Ford or Dijkstra's algorithm optimize some *metric*, such as the shortest path. In wireless networks this metric is typically hop count or some other measure of latency, as in DSDV [29] and DSR [30]. It is straightforward to generalize this metric to optimize for energy consumed at each hop, or per-hop costs.

By considering a per-hop cost that is a function of remaining node lifetime it becomes possible to handle routing in heterogeneous networks where some nodes have larger batteries or even wall power. Although most topology control protocols described above do not explicitly consider routing, by selecting which nodes remain active they implicitly influence routing.

Another factor that affects the energy consumption in routing is the link quality. Link-level retransmissions could largely increase the energy cost. A shorter path with many retransmissions may even worse than a longer path with more hops but fewer retransmissions. One way to handle this problem is to exclude bad links from route selection, so that the hop count metric can still be used. Another way is to add the link quality into the routing metric. Banerjee and Misra considered both the variable transmission power and link quality at each hop [31]. They defined a link cost that combines the link distance and the link error rate. Woo *et al.* examined the interaction of routing with link quality on Mica2 motes [32]. They proposed to use the number of total transmission (including retransmissions) as the routing metric.

In summary, research on energy-efficient routing is mainly focused on two aspects: minimizing energy cost per packet and balancing energy consumption in the network. The underlying MAC and topology control protocols can influence the design of the routing layer.

VI. ENERGY CONSERVATION IN TODAY'S AND TOMORROW'S APPLICATIONS

Having considered opportunities to conserve energy at each of these layers of the system, we conclude by placing them in the context of sensor networks that are being deployed today and that we expect may be deployed in years to come.

Habitat monitoring is a representative of current state-of-the-art for sensor network applications today [33]. Several dozens of Mica2 motes are placed to monitor a 500x500m area, augmented by a few computers with additional electrical and compute power and connectivity to the Internet. Deployment is done with some care to insure sufficient radio and sensing coverage.

It is informative to compare energy conservation in such an application. Radio transmission power is selected off-line, with deployment density and configuration in mind, to insure connectivity. On-line radio-power control is not necessary. Since target lifetimes are several months or an entire season, MAC-level power control is critical, using either S-MAC or low-power listening. The network is not dense enough to warrant on-line topology control, and with only a single extraction point for data, routing options are limited.

While this application indicates current practice, it is in many ways limited by current cost and deployment constraints. Today's sensors cost a few hundred dollars per node for hardware, and remote deployment, ongoing debugging and development make total costs higher still. As sensor prices fall and the infrastructure matures, denser deployments will become easier, making on-line use of transmission power control and topology control more feasible. Deployment of applications in less remote areas will motivate multiple connections to traditional networks, opening room for energy-conserving routing.

VII. Conclusions

Energy conservation is an active area of research in sensors networks. In this chapter we have briefly surveyed current work in transmission power control, MAC protocol design, topology control, and routing. As these areas move from theoretical studies, to laboratory experiments, to fielded systems, we are beginning to see the deployment of long-lived sensor networks and the fruition of this research.

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