Seminar: Verteilte Systeme – Sensor Network

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Energieeffiziente, drahtlose Sensornetze – Auswirkung der Hardware auf das Protokolldesign

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Abstract - The potential of collaborative, robust wireless sensor networks has attracted a great deal of research for its wide open range of application. As a major factor in wireless sensor networks, energy efficiency must be taken into account for its effect on the whole network performance and configuration.

This paper first analyzes the power consumption characteristics of typical sensor node architectures and identifies the various factors that affect the system lifetime. Then it discusses the implication of these hardware constraints on the protocol design of wireless sensor networks.

1. Introduction

Recent advances in micro-electro-mechanical systems (MEMS) technology, wireless communications and digital electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small in size and are able to communicate undeterred in short distances [1].

The application of this kind of wireless sensor networks can be found in the field of mobile computing and communications. A distributed, ad-hoc wireless micro-sensor network consists of hundreds to thousands of small sensor nodes scattered throughout an area of interest. Each individual sensor, containing both processing and communication elements, monitors the environment for events specified by the deployer of the network. One of the most important constraints on sensor nodes is the requirement of low power consumption. Due to the fact that sensor nodes are often distributed inaccessible in a certain environment, changes of batteries or static power supplies are not possible. Therefore, it is a big challenge to design an energy efficient wireless sensor network, which minimizes energy consumption and maximizes the lifetime of the whole system.

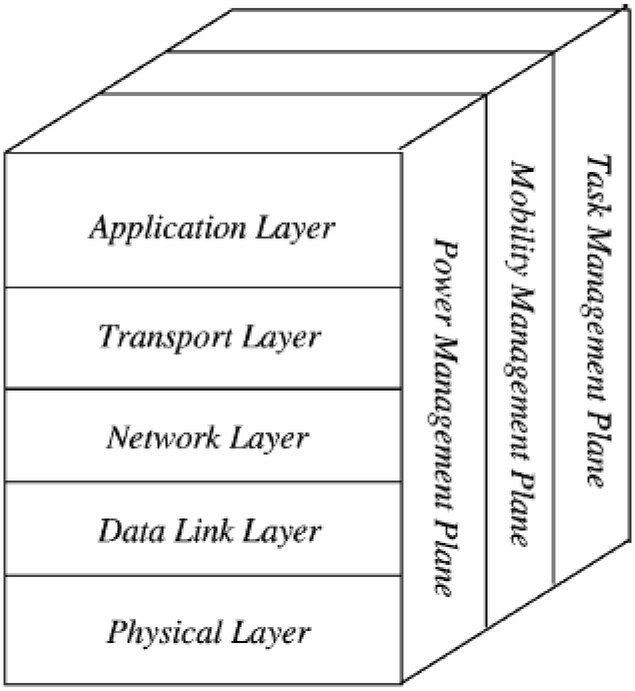

Figure 1. The sensor networks protocol stack

Neither the novel protocols, nor the algorithms designed for other ad-hoc or wireless networks can be adopted directly. As illustrated in Fig.1, besides the ISO-OSI protocol stack, extra controls, such as the power management plan, the mobility management plan, and the task management plan, should also be taken into consideration for protocol design. The power management plan monitors how a sensor node consumes its power. The mobility management plan detects and registers the movement of the sensor nodes. The task management plan balances and schedules the sensing tasks given to a specific region.

Design of an energy-efficient wireless sensor network is 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 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 [2].

This paper first analyzes the energy consumption of a typical sensor node which affects the design of protocol. Then it introduces data-link and media –access protocols that adapt parameters of the underlying physical layer in order to minimize energy. Finally, it discusses the energy-efficient network routing protocols.

2. Hardware Constrains

The first step in designing energy-aware sensor systems is to analyze the power dissipation characteristics of a wireless sensor node.

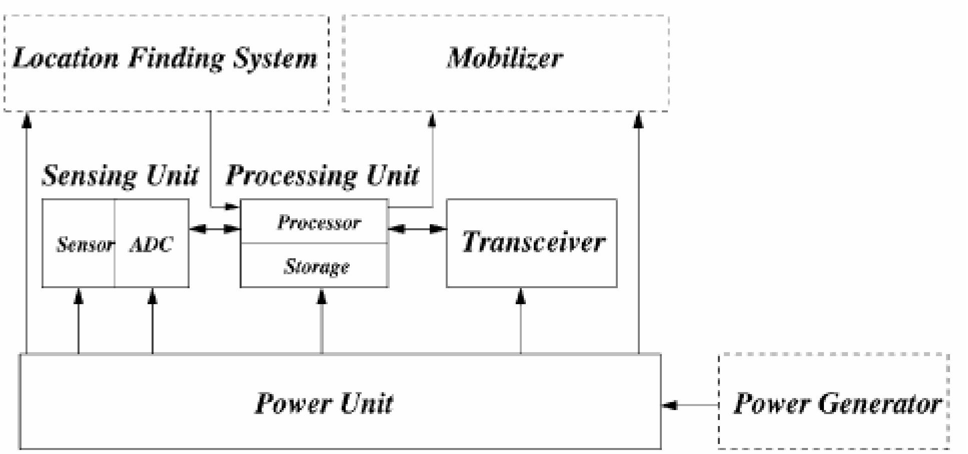

Figure 2. The components of a sensor node

Fig. 2 illustrates an example of sensor node architecture [1]. A sensor node usually consists four basic components: a sensing unit, a processing unit, a transceiver unit and a power unit. It may also have application-dependent additional components including a locating finding system, a power generator and a mobilizer.

The processing unit consists of a microprocessor or microcontroller. The transceiver consists of a short range wireless communication device. The sensing unit links the node to the physical world and consists of a group of sensors and actuators. And the power unit houses the battery and the dc-dc converter.

Power consumption of a sensor node can be divided into three domains: data processing, communication and sensing. All the three sub-systems will be analyzed in order to have an in-depth view of their influence on protocol design.

2.1 Processing Unit

The processing unit, which is generally associated with a small storage unit, manages the procedures for a sensor node to collaborate with other nodes to carry out the assigned sensing tasks. That is also why in some references it is also called microcontroller unit (MCU). Commonly used MCUs are static CMOS-based processors like Intel's StrongARM microprocessor and Atmel's AVR microcontroller.
The energy consumption of such kind of processors is modeled as:

$$E_{total} = E_{switch} + E_{leakage}$$

E_{switch} represents the switching energy and $E_{leakage}$ the leakage energy [3].
The switching energy is the energy required to switch between the internal states of the processor. It can be expressed as

$$E_{switch} = C_{total} V_{dd}^2$$

where C_{total} is the total capacitance switched by the computation and V_{dd} is the supply voltage. As circuit designers become more concerned with reducing power consumption, switching energy will become less dominant.
The leakage energy refers to the energy lost while the MCU is idle. It is expressed as

$$E_{leakage} = V_{dd}\left(I_0 e^{\frac{V_{dd}}{nV_T}} \right)(\frac{N}{f})$$

where N is the number of cycles the program takes to execute, f is the processor clock frequency and V_T is the thermal voltage. The leakage energy is an important parameter when designing a wireless micro sensor network. Experimental results have shown more than 10% of the total energy dissipation due to leakage. Thus, techniques to reduce the energy consumption penalty of low-duty cycle operations must be devised [4].
MCUs usually support various operating modes, including Active, Idle and Sleep modes, for power management purpose. Each mode is characterized by different amount of power consumption. Transitions between different operating modes are normally realized by high-level software-based techniques such as dynamic voltage scaling [5] and the progressive shut down of idle components. However, transitioning 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 of the sensor node. Further more, it has to be considered together with transition of different modes of radio transceiver, which will be discussed later.

2.2 Transceiver

A sensor node expends maximum energy in data communication using transceiver unit. The transceiver unit of sensor nodes may be a passive or active optical device or radio frequency (RF) device. Optical devices require an unbroken line-of-sight path for operation of free-space optical links, and are therefore not as widely applied as RF devices.

RF communications require modulation, filtering, demodulation and multiplexing circuitry. 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.

The average power consumption can be described by:

$$P_{radio} = N_{tx}\left[P_{tx}(T_{on-tx} + T_{st}) + P_{out}T_{on-tx}\right] + N_{rx}\left[P_{rx}(T_{on-rx} + T_{st})\right]$$

where $N_{tx/rx}$ is the average number of times per second that the transmitter/receiver is used, $P_{tx/rx}$ is the power consumption of the transmitter/receiver, P_{out} is the output transmit power, $T_{on-tx/rx}$ is the transmit/receive on-time (actual data transmission/reception time) , and T_{st} is the startup time of the transceiver. The startup time, being of the order of hundreds of micro-seconds, makes the startup power non-negligible. The $N_{tx/rx}$ will largely depend on the application scenario and the media-access control (MAC) protocol being used. T_{on-tx} can be further rewritten as *L/R*, where *L* is the packet size and *R*, the data rate [3].

In general, radios can operate in four distinct modes of operation: Transmit, Receive, Idle and Sleep. In most cases, operating in Idle mode results in significantly high power consumption, because even during idle, the radio electronics must be powered and decoding to detect the presence of an incoming packets [6]. Thus, it is desirable to completely shut down the radio rather than transiting into Idle mode. However, as shown above, the non-negligible startup time must also be taken into consideration. Under certain circumstances, frequently turning radio on and off would result in even more energy consumption than leaving the transceiver unit in Idle mode.

The selection of modulation schemes (e.g. binary vs. M-ary modulation), data rate (encoding schemes and packet size) must also be considered for protocol design, and, as will be shown later, will propagate to above lying layers.

2.3 Sensing unit

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 are several sources of power consumption in a sensor, including signal sampling and conversion of physical signals to electrical ones, signal conditioning and analog-to-digital conversion (ADC). In general, passive sensors such as temperature, seismic, etc., consume negligible power relative to other components of sensor node. Whereas passive sensors such as sonar rangers, array sensors can be large consumers of power. Due to the device specified characteristics of power consumption, the influence of sensor unit is ignored in this paper.

3. Impact of hardware on protocol design

Energy efficiency can be achieved on two levels: the unitary node-level and the network-level. On the unitary node-level, energy efficiency is secured by analyzing energy consumption of the hardware components, as mentioned in section 2, and choosing the right technology, e.g. radio technology and MCU, suitable for application. On the network-level, energy efficiency is realized by analyzing the network topology and finding the right distributed algorithms. The power consumption will be influenced in one way or another by every decision made during the design process.

3.1 Node level energy optimization

As a first step towards incorporating energy efficient wireless sensor networks, it is necessary to develop low-level protocols that enable low-power operations of individual sensor nodes in the network, based on the analysis of energy consumption by the related hardware components as shown in section 2. The technologies discussed here are: radio technology, MCU, dynamic power management and dynamic voltage scale.

3.1.1 Radio Technology

As discussed in section 2.2, the transceiver usually consumes the most energy of a sensor node. For RF devices, choice between different radio technologies has a significant influence on energy consumption. The design considerations of communicational protocol for energy efficiency are discussed hereafter.

3.1.1.1 Physical Layer Considerations

The physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation and data encryption.
One useful scale to characterize power consumption is the average power required to transmit one single bit [3]. Relevant factors are: distance between sensor nodes, carrier frequency and modulation.
Notice that generally, the output power required to transmit messages over a distance d is proportional to d^n [7], where *n* is the path loss exponent. *n* has a theoretical value of 2 (free-space), while experiments show that *n* is normally greater than 3 and is about 4 near ground[14]. This effect would be propagated to higher level protocol design of network topology and density, or vice versa. As a result, multi-hop networking is much more energy efficient than single hop (star topology) and therefore preferred for wireless sensor networks. For example, assume that the path loss exponent is 3. The energy consumed to transmit one bit over 10m is 2pJ, and therefore transmit one bit over 50m would be 10 pJ. Whereas sending it directly will cost about 1.25nJ, which is $5^3 = 125$ times more.
The tradeoff between antenna efficiency and power consumption leads to the choice of carrier frequency. In [8], a solution using UHF range (443 MHz in Europe and 915 MHz in North America) of the ISM (Industrial, Scientific, Medical) bands is preferred, resulting in an antenna efficiency of 15%. In general, lower frequencies achieve a longer scope but provide lower bandwidth.

The modulation scheme used by the radio is another important factor. As evidenced in (1), one way to increase the energy efficiency of communication is to reduce the radio transmit time. This can be accomplished by sending N ($M = 2^N$) bits per symbol, that is, by using M-ary instead of Binary modulation. This approach, however, will increase the circuit complexity and power consumption [9]. In addition, when M-ary modulation is used, the efficiency of the power amplifier is also reduced. This implies that more power will be needed to obtain reasonable levels of transmit output power and a more complex de-modulation hardware will be required. On the other hand, take Quadrature Amplitude Modulation (QAM) as an example, if the power amplifier is not increased, the distance between different symbols will be scaled down, which consequentially increases error rate.

The energy cost for transmitting one bit is:

$$E_{bit} = \frac{E_{st}}{L} + \frac{P_{elec} + P_{RF}(M)}{R_S \log_2 M}\left(1 + \frac{H}{L}\right)$$

as a function of the packet payload size *L*, the header size *H*, the fixed overhead E_{st} associated with the radio startup transient and the symbol rate R_S for an M-ary modulation scheme [2]. Replacing M by 2, the result complies to the binary modulation scheme. The optimal value of E_{bit} can be calculated given the value of E_{st}, P_{elec}, P_{RF}, R_S and H.

Various hardware specifications result in different R_S for energy minimization, independent from packet length.

As discussed in section 2.2, for a startup time dominant system, it is beneficial to operate with a packet size as large 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 optimal packet size is decided in the higher layer: the data link layer.

3.1.1.2 Data Link Layer Consideration

The data link layer deals with the multiplexing of data streams, data frame detection, medium access and error control. It ensures a reliable data transfer, which performs some error detection and correction.

Error correction schemes are used to maintain the bit error rate (BER) [3]. 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. A good error control scheme minimizes the number of times for a packet to retransmit, thus reduces the power consumed at the transmitter as well as at the receiver.

The BER can be shown to be directly proportional to the symbol rate R_S and inversely proportional to both the received signal to noise ratio (SNR) (E_S / N_0) [10] and the transmitter power level P_{out}. N_0 is the noise power spectral density (noise power in a 1 Hz bandwidth).

One widely used mode of error control in communication networks is forward error correction (FEC) [3].

Choosing between different MAC protocols is another challenging issue. Time division multiple access (TDMA) and frequency division multiple access (FDMA) could be two preferred options. Other more complex multi-access schemes may require e.g. shakehanding which increases latency and energy consumption.

TDMA schema dedicates full bandwidth to a single sensor for communication purposes, therefore minimizes the transmitting on time (T_{on-tx}) and reduces power consumption. However, time synchronization is required to maintain among the sensor nodes. This could be achieved by sending out synchronization packets (SYNC) or embedding preamble field in packet header.

FDMA scheme, different from TDMA, divides the signal bandwidth according to the number of sensors. Note that the network topology again plays an important role here for frequency re-use. The bandwidth of a single sensor is proportional to network density.

To choose between TDMA and FDMA schemes and find h_{opt}, the optimal number of channels which gives the lowest power consumption, the following formula can be used [3]:

$$h_{opt} \propto \sqrt{\frac{P_{rx}}{N_{tx} P_{tx}}}$$

The number of channels is determined by the ratio of the power consumption of the transmitter to the receiver. If the receiver consumes less power, a TDMA scheme is favored. Otherwise, FDMA is more appropriate.

3.1.2 MCU

Commonly used MCUs are Intel’s StrongARM, Atmel’s AVR, Intel 8051, ARM Thumb, SH Risc and IBM’s XScale microprocessor etc. While the choice of MCU is dictated by the required performance levels, it can also significantly impact the node’s power dissipation characteristics. Table 1 [11] compares the power consumption for execution and the working frequency.

Processor	Energy consumption pro Instruction (nJ)	Working Frequncy (MHz)
ATMega 128L	4	4
ARM Thumb	2.1	40
XScale	1.1	400
Cygnal	0.5	25

Table 1. Comparation of some MCU performances

Thus, the choice of MCU should be dictated by the application scenario, to achieve a close match between the performance level offered by the MCU and that demanded by the application.

3.1.3 Dynamic Power Management

As discussed in section 2.1 and 2.2, both processing unit and transceiver support different states of work modes with various energy dissipations. Once the hardware components have been designed, additional energy savings can be attained by using dynamic power management (DPM) [12] where the sensor node is turned into some sleep states if no event occurs.

Sleep state	Processor	Memory	Sensor, analog-digital converter	Radio
s_0	Active	Active	On	Tx, Rx
s_1	Idle	Sleep	On	Rx
s_2	Sleep	Sleep	On	Rx
s_3	Sleep	Sleep	On	Off
s_4	Sleep	Sleep	Off	Off

Tx = transmit, Rx = Receive

Table 2. Useful sleep states for the sensor node

Table 2 enumerates the component power modes corresponding to five different useful sleep states for the sensor node. Each of these node sleep modes corresponds to an increasingly deeper sleep state and is therefore characterized by an increasing latency and decreasing power consumption.

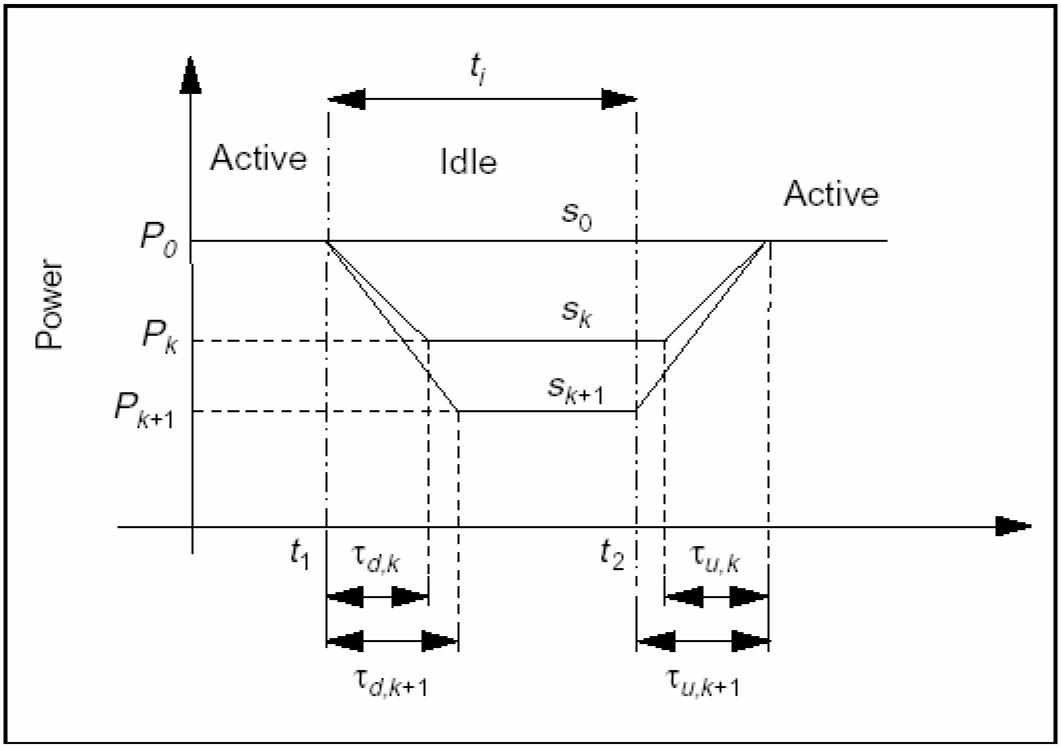

Figure 3. State transition latency and power

An algorithm to switch between sleep states is also provided in [12]. Figure 3 shows a time-power diagram of such a switch, and the energy saving from the states transition can be calculated by:

$$E_{save} = (P_0 - P_k)t_i - (\frac{P_0 - P_k}{2})\tau_{d,k} - (\frac{P_0 - P_k}{2})\tau_{u,k}$$

When state s_4 is reached, both sensor unit and the radio transceiver are turned off. Therefore, no events will be detected. These missed events require different strategies of switching algorithm to be applied due to application requirements. Options are: completely disallow s_4 state, or prediction of coming events.

3.1.4 Application Layer Consideration

While shutdown techniques, such as DPM as discussed above, save energy by turning off idle components, additional energy savings are possible also at the application layer.
The energy consumption for executing a program can be expressed as:

$$E \approx C \cdot W \cdot V^2$$

where C is the effective switching capacity, W is the number of instructions in the program and V is the supplied voltage of the MCU [13].
Dynamic Voltage Scaling (DVS) [5] adapts the processor's supply voltage and operating frequency dynamically to meet the instantaneous processor computational load, thus trades off unutilized capacity for energy savings. DVS-based power-management, when applicable, has shown possibility to achieve quadratic energy savings.
Code optimization is another solution. The gain of this method would be proportional to the portion of code being optimized.

3.2 Network Level Consideration

Low-power routing protocol concepts are presented in this section. Figure 4 [1] illustrates a typical network topology of wireless sensor network.

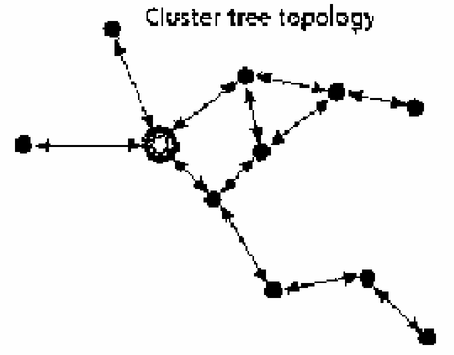

Figure 4. Cluster tree topology of a wireless sensor network

Sensor networks typically have a tree structure, which calls for a low-power routing protocol needed to route the data from the sensor to the high powered base-station, so-called *sink*. Such a multi-hop routing protocol should be optimized for minimum power dissipation at the wireless nodes where each node can be an information source, an information sink or a router.
One aspect of traffic forwarding is the choice of energy efficient multi-hop paths between source and destination. In this approach, each node maintains a routing table where the cost of each path is the power dissipated in transmitting information along that path. In order to deal with the dynamic nature of the network topology, the routing tables must be updated periodically. Since each node keeps track of every other node in the system and the optimal path to that node, this multi-hop protocol enables a point to point communication system that is "strongly connected". Thus, every node can transmit data

to the sink using various criteria: maximum available power, minimum energy, minimum hop or maximum minimum available power.

For data-centric routing or user-dispatch, the technique of data fusion could be applied. One exemplary method of data fusion is blind beamforming [15], where sensor aggregates data from its neighbors of selected number. Experimental results have shown the trade-off between quality and energy dissipation.

Another kind of protocol, i.e. a self-scheduling algorithm [16] based on the energy-conserving ad-hoc routing algorithm called geographical adaptive fidelity (GAF) [17], tries to maximize system lifetime by turning off some nodes in the network. With the assumption that all nodes share common sensing tasks and not all sensors are required to perform the sensing task if the sensor density is high enough, sensors could be clustered into grids according to their geographical location and therefore only one sensor of the cluster need to be used. Figure 5 shows an example of clustering using GAF algorithm.

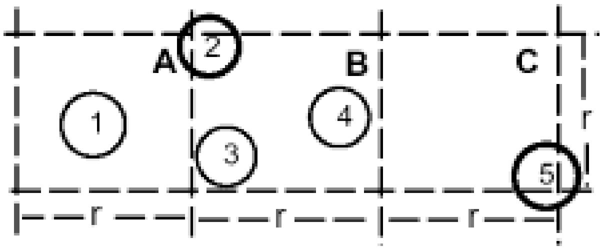

Figure 5. Example of virtual grid in GAF

As showed in Figure 5, node 1 can reach any of 2, 3, or 4, and 2, 3 and 4 can all reach 5. Therefore node 2, 3 and 4 are equivalent and two of them can sleep. GAF suggests that network lifetime increases proportionally to node density.

3.5 Application Consideration

On this level of design, when underlying hardware constrains and lower layer protocols are all presented, it is possible to reduce power dissipation by system partitioning. Due to application requirements and specification, algorithms could be designed to partition computation, i.e. to achieve a better overall performance. [18] provides an example of system partitioning with a sensor network application scenario of vehicle movement tracking.

Furthermore, on this level, code executed on each sensor could be optimized, which also reduces energy consumption during execution.

4. Conclusion

This paper introduces and analyzes factors and techniques at various levels of the system hierarchy that must be taken into consideration for the design of an energy efficient wireless sensor network. Due to the current hardware constrains, energy dissipation of computation, data transmission and sensoring all have significant impact on the protocol design. Choice between different processors, radio transceivers and network topologies are therefore critical to energy efficiency, system lifetime and performance.

References

[1] I.F. Akylidiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, Wireless sensor networks : a survey, Computer Networks (Elsevier) Journal, pp.393-422, March 2002

[2] V. Raghunathan, C. Schurgers, S. Park, M. Srivastava, Energy-aware wireless microsensore networks, IEEE Signal Processing Magazine, 2002

[3] E. Shih, S. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, A. Chandrakasan, Physical Layer Driven Protocol and Algorithm Design for Energy-Efficient Wireless Sensor Networks, 7th Annual ACM SIGMOBILE Conference on Mobile Computing and Networking, Rome, 2001

[4] V. De, S. Borkar, Technology and Design Challenges for Low Power and High Performance, ISLPED '99, pp. 163-168, 1999

[5] T.A. Pering, T.D. Burd, R.W. Brodersen, The simulation and evaluation of dynamic voltage scaling algorithms, ISLPED, 1998, pp.76-78

[6] O. Kasten, Energy Consumption, www.inf.ethz.ch/~kasten/research/bathtub/energy_consumption.html, ETH Zuerich, 2001

[7] E. Shih, B. Calhoun, S. Cho, A. Chandrakasan, Energy-Efficient Link-Layer for Wireless Microsensor Networks, 7th Annual ACM SIGMOBILE Conference on Mobile Computing and Networking, Rome, 2001

[8] A. Porret, T. Melly, C. Enz, E. Vittoz, A low-power low-voltage transceiver architecture suitable for wireless distributed sensors network, IEEE International Symposium on Circuits and Systems, Geneva, 2000

[9] C. Schurgers, O. Aberthome, M. Srivastava, Modulation Scaling for Energy Aware Communication Systems, ISLPED '01, 2001

[10] P. Lettieri, C. Fragouli, M. Srivastava, Low Power Error Control for Wireless Link, in Proc. Mobicom, 1997, pp. 139-150

[11] M. Srivastava, Power-aware Design, EE202A, 2002

[12] A. Sinha, A. Chandrakasan, Dynamic Power Management in wireless sensor networks, IEEE Design & Test of Computers, 2001

[13] C. Hsu, U. Kremer, M. Hsiao, Compiler-Directed Dynamic Voltage/Frequency Scheduling for Energy Reduction in Microprocessors, ISLPED '01, August 6-7, 2001

[14] K. Sohrabi, B. Manriquez, G. Pottie, Near-ground wideband channel measurements, IEEE Proceedings of Vehicular Technology Conference, New York, 1999

[15] A. Chandrakasan, R. Amirtharajah, S. Cho, J. Goodman, Design Consideration for Distributed Microsnesor Systems, Proc. IEEE Custom Integrated Circuits Conf. (CICC), San Diego, CA, May 1999, pp. 279-286

[16] D. Tian, N. D. Georganas. "A Coverage-Preserving Node Scheduling Scheme for Large Wireless Sensor Networks", Mobicom Workshop on Wireless Sensor Networks and Applications (WSNA 2002), September 2002, pages 32-41

[17] Y. Xu, J. Heidemann, D. Estrin, Geography-informed Energy Conservation for Ad Hoc Routing, MOBICOM'01, 2001

[18] D. Estrin, R. Govindan, J. Heidemann and S. Kumar, Next Century Challenges: Scalable Coordination in Sensor Networks, Proc. of ACM MobiCom'99, August 1999