Investigations on Power-Aware Solutions in Low Power Sensor Networks

S. S. Vidhya and Senthilkumar Mathi

Abstract Power management is a very vast topic and the solution spans around hardware and software approaches. The power efficiency of IoT low-power devices becomes an important component of modern communication environments since it is very costly or impossible to replace or change device batteries in deployed environments. Energy management in sensor networks is an open challenge to researchers Hence, this article is investigated the power management solutions introduced in various literature. A detailed investigation of energy harvesting-based techniques and network-based solutions for efficient utilization of available energy is explored. The paper also highlights the recent advancement in technologies to improve battery life by adding low power components, circuitry, and low power communication protocols such as ZigBee, RPL, wirelessHART, Bluetooth low energy, and LoRAWAN. The analysis drawn from the investigation is the combination of the power provisioning approach with power control-based solutions are the best suited for designing power-efficient schemes.

Keywords Sensor network · Low power networks · ZigBee · RPL · WirelessHART · Bluetooth low energy · LoRAWAN

1 Introduction

A wireless low-power network is composed of tiny sensor nodes powered by a battery. The key component of sensor networks [1] is processing module, sensing module, transceiver module, and power unit as shown in Fig. 1. Energy management in low power nodes is achieved through various protocols to manage power supply units and efficient utilization of available energy in a sensor node. To tackle the

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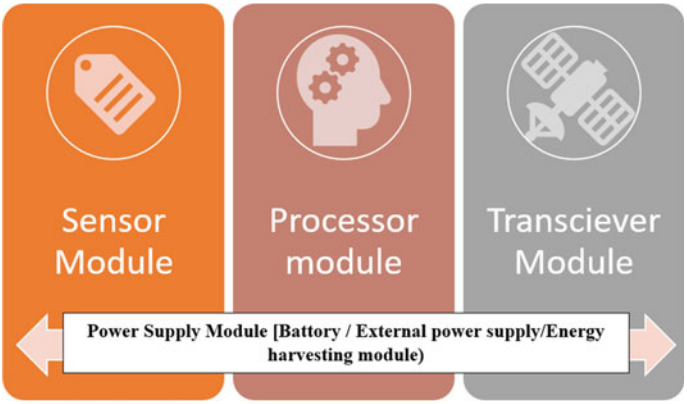


Fig. 1 Sensor node—architecture

energy scarcity in sensor nodes balanced management between use and supply is required. The power consumption modules in a sensor node and its rate of energy usage are shown in Fig. 2. The transceiver unit is the most energy-hungry module in a sensor node. So that the software-based solutions are mainly concentrated on the communication part.

The common power source for a sensor node is a battery. Consumer battery lithium-ion is suitable for common applications such as smart homes, parking lots, etc. But extreme environments, like a cold chain which is used to monitor frozen foods, pharmaceuticals, etc. demand bobbin-type batteries. Common batteries are prone to capacity losses (e.g., 30% loss after 1000 cycles). The degradation is directly proportional to environmental conditions such as temperature, humidity, etc. Another problem that reduces the life of a battery is self-discharge. The loss rate depends on the temperature and chemical reactions inside the cell. The constraints of battery supply led the researchers to propose alternate power provisioning techniques by using ambient energy [2]. These energy harvesting techniques have some limitations

Fig. 2 Energy consumption modules in the sensor node

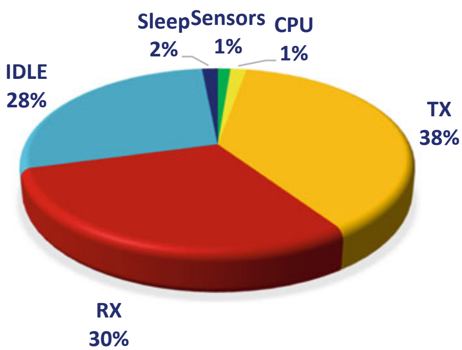
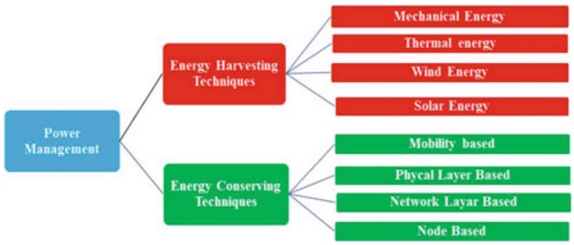


Fig. 3 Top tier division



since there are some situations where the harvesting chance is less than the required power [3].

In the present work, the energy management solutions are divided into two namely, energy harvesting and energy conserving. The top-tier taxonomy described in this literature is shown in Fig. 3. Most power management schemes considered that data collection consumes less power than data transmission. Hence, many research works happened in the area of transmit power control and routing-based solutions [4]. The challenges in network power management are as follows.

(1) Limited power source such as battery powered
(2) Sensor network deployment areas such as dense forest, mining area, and smart furnace.
(3) Dynamic network topology due to adhoc nature
(4) Node mobility in applications like cattle monitoring.

2 Energy Harvesting Techniques

One of the solutions to overcome the energy constraint issue of low power networks is energy harvesting techniques. Different sort of energy-producing techniques such as solar, wind, thermal and mechanical energy converts different sources of energy to electrical power. The general modules of a harvesting system are shown in Fig. 4. The photoelectric cells are used to convert light energy to electric energy. It will not work efficiently during cloudy and night time. The wind-based system uses turbines to produce electric power. The thermal system uses mechanical resources with an electrostatic generator. The majority of the systems use rechargeable batteries to store generated power.

The most commonly used resource is light energy. It can be artificial or natural light. This resource is a cheap, pollution less, inexhaustible and clean source of energy applicable for outdoor IoT applications. The amount of power harvesting will depend on the light intensity, atmospheric conditions and the cell area. Another parameter is the incidence of light. For full efficiency, the light source and the cell array should be perpendicular. The disadvantage of this system is (i) not suitable for indoor (ii) Depends on light and incident angle. Kansal et al. [5] conducted a study

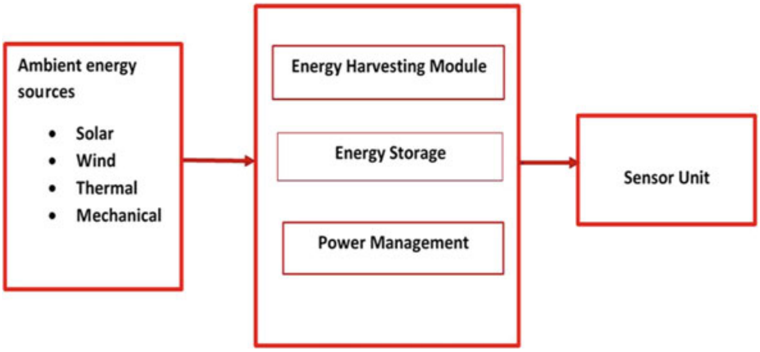


Fig. 4 Components of energy harvesting system

of voltage properties of different solar cell and associated storage devices in different environments. Similar works based on solar energy is shown in Table 1.

In most of the solar power-based works hybrid schemes are used, that is to manage the harvested energy efficiently with hardware or software-based modules. The energy generating module in cooperation with the energy management module is presented in [8–11]. A better choice of power management is based on prediction-based approaches. This can be achieved in two different ways namely, predicts the future energy needs of the communication nodes and predicts the future energy production from the harvesting sources. Table 2 summarises light energy-based hybrid schemes. Wind energy is another popular approach in the field of low power

Table 1 Energy harvesting solutions: Light energy-based

Source of energy /Node	Storage	Merit	Shortcoming
Heliomote [5]	NiMH battery	• Harvesting aware performance scaling algorithms • Select paths that have more solar availability	• Harvesting efficiency is low, single energy resource based
Ambimax [6]	Sup-capacitor	• Computes maximum power point tracking, the semiconductor is charged based on this • Harvesting is done from the combination of solar and wind	• Efficiency depends on the deployment area
Prometheus [7]	Sup-capacitor	• Intelligently manages energy transfer • Lifetime is maximized by managing mote power levels	• No MPPT circuit

Table 2 Energy harvesting solutions: Light energy-based hybrid schemes

Research work	Strategy used	Merit	Shortcoming
Abbas et al. [11]	Analytical model	Used Maximal Power Transferring Tracking (MPTT) algorithm, predicts upcoming energy, and dynamic selection of transmit power	Not discussed network-level energy management
Zhang et al. [10]	Duty cycle based	Energy efficiency is improved through opportunistic duty cycling. Adjusts duty cycle with local history	Harvesting module and management modules are independent
Dehwah et al. [9]	Routing	Dynamic programming-based routing policy optimization	High computation power
Wang, J et al. [8]	Node distribution	Distributed approximation algorithm-based solar head placement strategy and wireless charging of other nodes	Efficiency depends on the deployment area
Kosunalp [18]	Energy prediction	Q-learning based solar energy prediction Improved prediction accuracy	High computation power
Yang et al. [19]	Energy prediction	Each node energy consumption-based distributed power-aware data collection scheme	Prediction based on weathercast

networks. It requires bulky hardware, which lowers the feasibility of sensor network implementations. The proposals made in [12–17] is based on wind power. Most of the proposals are based on a prediction approach since the availability of wind will depend on the weather and the previous wind history.

Vibration-based works are widely used in WSNs, especially in body area networks [20] and aquatic sensor networks [21]. The power source used in these works is piezoelectric materials. Mechanical stress is converted into electric energy from motion or vibration. The paper proposes the conversion of vehicle vibration into electric energy in smart roadways [22]. Electrostatic based energy generation module uses the principle of distance change between two capacitive plates kept at a constant charge. During vibration, the distance between the plates changes and the energy is produced from the model.

The research works in [22–26] proposed mechanical energy based harvesting system for low power networks. Knight et al. proposed a thermal energy-based scheme, the thermostatic device is used as a power module. It is also applicable in the sensor networks deployed on water surfaces. The works based on power resources other than light is listed in Table 3.

3 Energy Conserving Techniques

The innovative sensor applications in the area of technology-assisted sensor networks are found to be the most demanding innovation in the area of technology-assisted living.

The power harvesting assisted sensor nodes are always not a good solution for all the applications because of extra hardware requirements along with the actual nodes. In this section, the various approaches proposed by researchers to manage battery dependant node's efficiency for keeping the network live are discussed. Here, the paper presents a broad idea of different approaches done in network protocols. Such a scheme can be categorized into three categories based on its characteristics as given in Fig. 5.

Data-driven approaches—energy management through data-driven concentrates on collected samples. This is achieved through two basic schemes (i) sensor data transmission based and (ii) sample data acquisition based. Data compression is one of the techniques that can be adopted to reduce the size of sending data.

Many compression algorithms are proposed for minimal centering power sensor nodes [27–29]. An alternative approach in the data reduction is, the part of sample data can be predicted so that the transmission rate towards the sink node can be lowered. Constant prediction [30], Exponential smoothing [31] and ARIMA [32] are the proposed prominent works based on this scheme.

Routing based approaches—one of the promising network-level energy management technique is energy-aware routing schemes. Variant transmitting modes and cluster management are the auspicious approaches in this area [33–35]. The sensor nodes are divided into different clusters with single or multiple CH to reduce the communication distance. This cluster level communication management can reduce energy depletion between sink node and data collection points. Most of the schemes try to select cluster head intelligently for the efficient management of energy [36–39]. One such approach is LEACH [40]. Many extensions to this protocol are proposed in [41–43]. Recently some variants of hierarchical routing such as tree-based, location-based and chain based are proposed [44, 45] for managing energy efficiency. The routing schemes such as energy-efficient routing [46], Ad-hoc on-demand distance vector routing (AODV) [47], routing protocol for low power network (RPL) [48] etc. ensures low energy consumption at communication nodes. Geographical random forwarding is a location-aware approach for selecting relay nodes [49].

Duty cycling based approaches—the network life can be increased by switching the node state between sleep and active mode. Most of the research works in this area focused on variant sleep node selection criteria. Adaptive self-configuring follows such an approach [50]. One of the efficient approaches proposed in [51, 52] is making some number of redundant mobile nodes to sleep and keeping others in

Table 3 Energy harvesting solutions: Non-solar energy resources

Scheme	Strategy used	Merit	Shortcoming
Wind energy [14]	Prediction based: weather-conditioned moving average	Used MPTT algorithm, predicts upcoming energy availability, Dynamic selection of transmit power	Single resource dependency
Wind energy [15]	Prediction based: wind energy predictor (WEP)	Wind energy availability is predicted based latest energy generation information Improved wind energy conservation rate	Single resource dependency
Wind energy [16]	Prediction based: weather forecast based duty cycle power management	Weather forecast based wind energy availability prediction and storage policies based on the predicted value	Weather forecast-based prediction
Wind energy [17]	Non-predictive MPTT	MPTT circuit-based energy optimization with energy storage circuit	Depends on wind availability
Wind energy [20]	Energy prediction	A proper rectifier bridge is selected using predicted power and follows an adaptive strategy	Energy management and harvesting modules are independent
Wind energy [21]	MPTT based	Low power management hardware circuit using MOSFETs to efficiently manage low wind speed condition MPTT is done through resistor emulation	Depends on wind availability
Mechanical [23]	Combined energy-aware interface	Vibration-based harvesting module and software-based energy flow management	Huge size
Mechanical [22]	Road vibration	Vehicle speed-based road vibrational frequency piezoelectric cantilever beams	Hardware size is high
Mechanical [24]	Human motion-based	Statistical characteristics of human motion stochastic model	Used for body area networks
Mechanical [25]	Water pressure based	Water pressure is applied to piezoelectric material and used for underwater communication	Applicable for specific applications

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Table 3 (continued)

Scheme	Strategy used	Merit	Shortcoming
Thermal [26]	Thermostatic device-based	Solar energy is converted to electric power	Applicable for specific applications

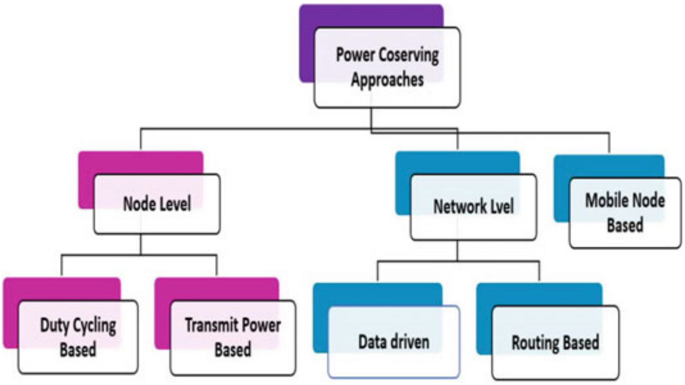

Fig. 5 Energy conserving approaches

wake-up mode. In research work, [53] proposes a sleep scheduling scheme-based linear distance approach. The sleep decision is taken by a node based on the probability which is proportional to the distance from the sink node. In the basic energy-conserving scheme [54] three states are defined namely active, sleep and idle for each node. Based on the routing or application layer information, nodes switch among these states. Dynamic sensor MAC [55] proposed a dynamic sleeping cycle based on power availability at nodes and network latency. The major problem with these schemes is latency unless the scheduling scheme chosen is not effective.

Mobile node-based approaches—the mobility in a low-power network is termed micro-mobility since the network contains few mobile nodes and the mobility environment is a limited area. In the present work, Greedy maximum residual energy [56], proposed a mobile sink node to collect sensor information from nodes. Another approach is made in [57], which is based on a mobile relay, and data collection is done through message ferries. These nodes move around the fields, collect data and send it to the destination node. In the literature [58] and [59] has done an experiment based study to show the effect of transmit power and energy consumption in adhoc networks. The results are shown in the Figs. 6 and 7. Various power conservation-based schemes discussed are summarized in Table 4 (Fig. 6).

Low power network protocols—as the popularity and applications of low power networks are increasing day by day, different standard protocols are exclusively defined for low power networks. The characteristics of the network protocols are

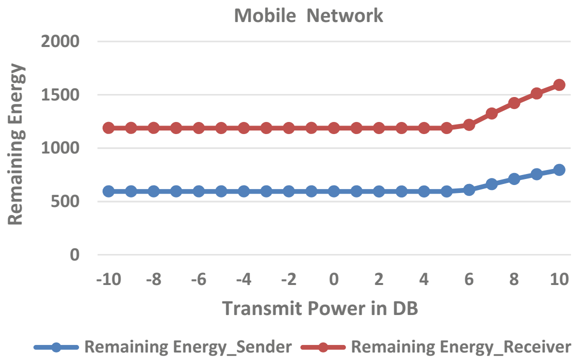

Fig. 6 Remaining energy for different transmit power in mobile network

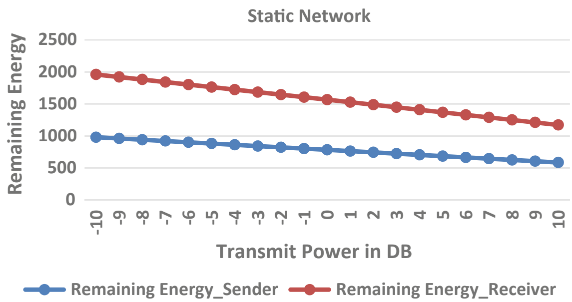

Fig. 7 Remaining energy for different transmit power in static network

given in Table 5. Conventional communication protocols are defined for sending a large amount of data (Fig. 7).

Traditionally the sensor nodes are dealing with small scalar values like pressure, temperature, humidity, etc. It becomes wastage of energy and bandwidth if traditional protocols are used to communicate with these small-sized data. So, the protocols like low power Wi-Fi, Bluetooth Low Energy, Zigbee, *Z*-Wave, and LoRaWAN [65–69] are introduced for low power communication networks.

The inferences made from the investigations are as follows. (1) The power management schemes in low power networks can be categorized into two: energy harvesting and energy conserving. (2) The energy harvesting schemes are efficient in terms of long-life networks. (3) The efficiency of energy harvesting schemes depends on (i) deployment environments and (ii) the proper management and storage of harvested energy, since the availability of common resources like light, wind, etc. depends on environmental factors. (4) The network-based energy conserving protocol demands prior knowledge of network power distribution and its consumption. (5) Duty cycling-based schemes are prone to delay because the sleep node selection and synchronization is a hurdle. (5) The power level management needs proper power level selection for efficient communication.

Table 4 Summary of energy-conserving solutions

Protocol	Scheme	Merit	Shortcoming
AP-routing [30]	Data-driven approach	Predicts next probe time based on the environmental changes	Low data accuracy
SIP [31]	Data-driven approach	Data filtering of sensed data	Applicable for engine monitoring applications
ARIMA [32]	Data-driven approach	Sensor node readings are predicted using the time series model	Data accuracy depends on the prediction
EECRP [33]	Routing based	Cluster heads are rotated based on the energy load	Node density is not considered
LEACH-AP [34]	Routing based	Nearest neighbor selection from the received power and distance formula	Needs information about node position
TEAR [36]	Routing based	Cluster head (CH) selection is based on node initial energy, residual energy, and traffic load	Node density is not considered
PSO-UFC [37]	Routing based	Swarm optimization-based CH selection	Node density is not considered
EF—LEACH [38]	Routing based	Remaining energy-based dynamic CH change	Node density is not considered
RARZ [41]	Routing based	Remaining energy-based CH selection and location-based routing	Node density is not considered
SEECH [42]	Routing based	Separates CH and relays based on node eligibility, a distance-based scheme is employed	CH energy is not considered
LA-MHR [42]	Routing based	Learning automata-based CH selection	High computation
EQR [46]	Routing based	Data prioritization and mobile sink-based	Low data accuracy
SPEED [47]	Routing based	Feedback control and geographic forwarding	Needs the knowledge of node location

(continued)

Table 4 (continued)

Protocol	Scheme	Merit	Shortcoming
GeRaF [49]	Routing based	Location and node contention-based data forwarding	Needs the knowledge of node location
ASCENT [50]	Duty cycling	Adaptively elects active nodes based on node density	Chance of prolonged active state of a single node
LDS [53]	Duty cycling	Linear distance-based sleeping node selection	Chance of prolonged sleep state of a single node
AODV and DSR [54]	Duty cycling	Application-level information and node density-based sleep node selection	intra-layer communication is needed
DSMAC [55]	Duty cycling	Analytical based duty cycle adjustment	Computation overhead
Variable-range transmission power control [60]	Node level	A model based on the routing protocol and signaling overhead	Service message overhead
DDPC [61]	Node level	Dynamic varying of transmission power	Power level is varied based on a feedback mechanism
Power Control Protocol [62]	Node level	Different power levels for service messages and data messages	Power reduction is based on service message count
EPARN [63]	Node level	Residual energy and expected future energy needs based routing	Computational overhead
CLPC [64]	Node level	Average RSSI-based routing	RSSI is environment dependant
Controlled sink mobility [56]	Mobile node based	Route selection using mixed-integer linear programming and the sink movement based on Greedy algorithm	Computational overhead

4 Conclusions

This investigation work presented different energy-aware schemes in IoT network communication. The review is done in two directions: energy harvesting approaches and energy-conserving techniques. A tabular-based summary with performance metric comparison is presented for all energy management kinds of literature discussed in this work. It is recommended that a hybrid scheme that combines energy harvesting and energy-conserving techniques, which will be the best choice

Table 5 Power consumption and properties of low power network protocols

	Power consumption			Properties
	Sleep (μ W)	Transmit (mW)	Receive (mW)	
Low power Wi-Fi [65]	300	350	270	Dynamic energy consumption, high throughput, penetration through walls, and other obstacles, range up to 1 km
Bluetooth Low Energy [66]	8	60	53	Low latency, high security, high speed, Range up to 100 m
ZigBee [67]	4	72	84	Self-organization, low cost, range up to 100 m, and IPv6 support
Z-wave [68]	3	70	65	RF-based, less radiation, highly reliable, range up to 100 m
LoRaWAN [69]	1	77	18	Wide coverage up to kilometers, a single node can handle thousands of devices, low cost, point-point communication with end devices

for increasing network lifetime. However, energy management is still an open challenge to researchers, and lots of studies are required towards the efficient functioning of low power networks.

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