A Comparative Study of Energy Consumption Sources for Wireless Sensor Networks

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Abstract

With the development of MEMS and CMOS technologies, the implementation of a huge number of wireless distributed micro-sensors that can be simply and rapidly deployed to form highly redundant, self-configuring, and ad hoc sensor networks. Sensor nodes are generally battery- devices, the critical facets to face concern are how to minimize energy consumption of nodes, so that the lifetime of sensing nodes can be maximized. The first step to achieve this goal is to know completely the sources of energy consumption in wireless sensor networks. In this paper, sources of energy consumption at various communication layers have been studied and investigated. Moreover, the energy consumption for the components of a typical sensor node and the impact of communication protocols stack on the energy consumption are discussed. In the sequel, the sources of energy consumption in each communication layer individually are studied. Then, a survey has been provided for existing energy models and the classification of these models into physical layer, MAC layer and cross-layer energy models.

Keywords: Wireless sensor networks, energy consumption, energy modeling, physical layer, cross-layer

1. Introduction

The combined and separated research advancement in the fields of computing, communication, and sensing has driven the research efforts in wireless sensor networks (WSNs) in recent years. Typically WSNs consists of interconnected sensor nodes, from a few to several thousand that are capable of not only sensing and computing, but also communicating with each other[1]. These networks are found usage in various areas, such as industrial process automation, environmental monitoring, and field surveillance[2].

Different from the traditional networks, the main characteristics of aWSNs are short-range transmission, high sensor density, and low data rate. Depending on the application, there can also be stringent latency and bit error rate requirements. As a result of the random distributed nature and the large density of WSNs, battery replacement is a hard task. Actually, a major issue that prevents WSNs to be used in various application areas is the short battery life. Consequently, maximizing the battery lifetime of the sensor nodes is significant. The first step to achieve this goal is to know completely the sources of energy consumption in wireless sensor networks.

The functionality of a WSN node is generally executed through microelectronics of sensing unit, processing unit, communication unit and power unit [3]. Each unit has three conditions; active, idle and sleep. Energy consuming in each unit depends on the state of the unit. The communication system, used to transfer information between the sensor nodes, is a main block in every WSN system. Practical communication system design is aided by communication protocol stack. The communication protocol stack is a five-layer architecture, where each layer is responsible for specific sub-systems. The communication protocol stack is made up of a physical layer, data link layer, network layer, transport layer

and application layer. Each layer has its own characteristics and has its effect on the energy consumed. The physical layer is responsible for frequency selection, carrier frequency generation, modulation, signal detection and data encryption. The function of the data link layer is how dose node communicates with other nodes, so it's related to retransmission due to collisions, overhearing. The network layer is responsible for choosing the route between source and destination. The transport layer helps to keep the flow of data if the application needs it. Application layer crossing point directly with the applicationand it makes common facilities for the application processes, and problems requests to the transport layer.

Cross-layer is targeted to give-and-take of information over layers to reach significant performance enhancement by developing the interaction between different protocol layers [4].

In this paper, the energy consumption of each hardware unit of a typical sensor node is discussed and some example unites are presented. Regarding to the communication protocols, the impact of communication protocols stacks of WSNs on energy consumption is discussed. Moreover, a survey of existing energy consumption models has been provided. These models have been classified into physical layer energy models, MAC layer energy models and cross-layer energy models.

The rest of this paper is organized as follows. Section 2 discusses judgment metrics on the WSNs. Section 3, is dedicated to the hardware of sensor node and energy consumed in each unit. Section 4, discuss the sources of energy consumption in each communication layer individually. Section 5, provide a survey of existing energy models in WSNs. In Section 6, we conclude the paper with a summary and give possible directions for the future work.

2. Metrics in the WSNs

There are several metrics that are used to judge the quality of WSN systems. Some of these include;

1)   Network Lifetime (LT): which is a significant metric depending on several factors, including lifetime definition, energy consumption model, protocols, and network architecture, channel characteristics, and data collection initiation [5].

2)   Energy Efficiency (EE): which aims to reduce the amount of energy consumption for a given task (e.g. Energy efficient clustering scheme (EECS))[6].

3)   Energy-Per-Useful-Bit (EPUB): which captures overhead due to physical layer modulation [7].

4)   Latency: which can be defined as the time required to send a packet through a network from source to the sink [8].

The network lifetime becomes a critical metric used to judge the quality of WSNs, where several techniques have been made to increase the network LT. Some of these include power aware storage, energy-aware MAC protocols, duty-cycling schemes, redundant placement of nodes, data dissemination and routing protocols, and tiered system architectures [9]. As we mentioned above that the network lifetime depends on the definition, so we listed below some common definitions of network lifetime which are used in previous work:

Definition 2.1: Network lifetime can be defined as the time duration from the beginning of the network job to the moment when the first nodedies [9].

Definition 2.2: Network lifetime is the maximum time after which the desired network performance cannot be achieved [10].

Definition 2.3: Network lifetime is defined as the time period during which the data rate is preserved above a minimum required datarate [11].

Definition 2.4: Network lifetime is defined as the time duration from start the first transmission in the WSNs to the moment when the number of nodes which have not finished their remaining energy falls below a threshold, which is depended on the type of application [5].

Definition 2.5: Network Lifetime can be defined as the time period, which the required Signal-to-Noise Ratio (SNR) at the sink is met with a specific probability [12].

3. Hardware of Sensor Node

The functionality of a sensing node is generally implemented through four basic units which are; transceiver, processing, sensing and power units as shown in Figure 1. The transceiver unit allows the sensor node to interconnect with other sensor nodes. The processing unit is used to allow management and data processing in the sensor node. The function of sensing unit is observing specific phenomenon. The power unit is used to provide the system supply voltage and it can be supported by an energy harvesting unit such as small-scale wind mills or solar cells. Also, it may have optional unit such as mobilize subsystem and location finding system[13-14]. Therefore, the average energy consumption per unit time of sensor node can be express as:

$$E_{hw} = E_{tran} + E_{comp} + E_{sen} + E_{pow}$$

where E_{tran}, E_{comp}, E_{sen} and E_{pow} are the energy consumed in communication subsystem, computing subsystem, Sensing subsystem and Power subsystem, respectively.
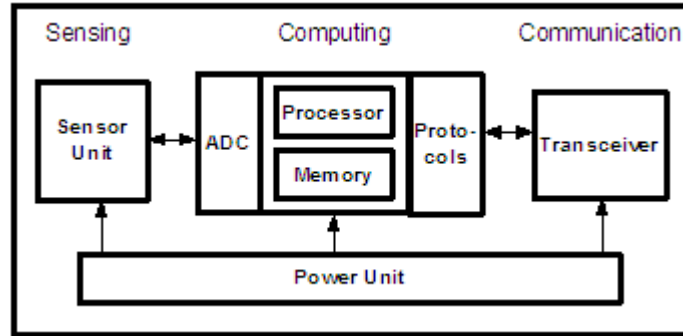

Figure 1. Sensor Node Hardware Architecture

3.1. Communication Subsystem

The Communication Subsystem is composed of transmitter circuit, receiver circuit, and an antenna which are used to send and receive packets. The purposes of the Communication Subsystem are the selection of a frequency channel, a transmit power, the modulation scheme, symbol synchronization, and clock generation.The energy consumption for a certain communication subsystem in sensor node can be expressed as [15]:

$$E_{tran} = P_{ont}T_{on} + P_{onr}T_{on} + P_{tr}T_{tr} + P_{sm}T_{sm} + P_{dc}T_{on}$$

where the total time duration is divided between the communication active mode T_{on}, transient mode T_{tr} and sleep mode T_{sm}. During sleep mode, the power consumption P_{sm} is dominated by the leaking current of switching transistors. This term is often neglected, i.e. P_{sm} can be set to zero. The transient-mode time arises mainly from the frequency synthesizer settling time, and the settling time for other devices such as a mixer and power amplifier can be neglected and power consummation at thismode is P_{tr}. During active mode, power is consumed at digital

circuits (P_{dc}), analog circuits at the transmitter (P_{ont}) and receiver side (P_{onr}). The analog-circuit power terms can be expressed as

$$P_{ont} = P_{Dct} + P_{Act} + P_{amp} + P_t = P_{to} + (\alpha + 1)P_t$$

$$P_{onr} = P_{Dcr} + P_{Acr} + P_{LNA} = P_{ro}$$

where P_{Dct} and P_{Act} are the power consumptions of the digital circuit at transmitter side and the analog circuit at transmitter side, respectively, the two components can be modeled as a constant, P_{to}. P_{amp} and P_t are the power consumptions of the power amplifier and transmitted power. $\alpha = \xi/\eta - 1$ with ξ and η being the drain efficiency and the peak-to-average ratio, respectively. Similarly, P_{Dcr}, P_{Acr}, and P_{LNA} are the power consumptions of the digital circuit at receiver side, the analog circuit at receiver side, and LNA, respectively, the three components can be modeled as a constant, P_{ro}. The characteristics of some of low power transceiver units are summarized in Table 1 [16–18].

Table 1.Radio Features, Current Consumptions, and Energy Efficiencies

Name	Manufacturer	Band (MHz)	Data rate (kbps)	Sleep (μA)	TX (mA)	RX (mA)
MRF49XA	Microchip	433/868/915	256	.3	15	11
MRF89XA	Microchip	915	25	.1	25	3
MCMRF24J40	Microchip	2400	250	2	22	18
AT86RF212B	Atmel	700/800/900	1000	.2	18	9.2
NSnRF2401A	Nordic Semiconductor	2400	1000	0.9	13.0	19.0
NSnRF24L01	Nordic Semiconductor	2400	2000	0.9	11.3	12.3
NSnRF905	Nordic Semiconductor	433-915	50	2.5	12.5	14.0
nRF24L01+	Nordic Semiconductor	2400	250	.9	11.3	13.5
RFMTR1001	SRFMonolithic	868	115.2	0.7	12	3.8
RFMTR3100	SRFMonolithic	433	576	0.7	10	7.0
SEXE1201A	Semtech	433	64	0.2	11.0	6.0
SEXE1203F	Semtech	433-915	152.3	0.2	33.0	14.0
TICC2420	Texas Instruments	2400	250	1	17.4	18.8
TICC2500	Texas Instruments	2400	500	0.4	21.2	17.0
TICC1000	Texas Instruments	433-915	76.8	0.2	10.4	9.3
TICC1100	Texas Instruments	433-915	500	0.4	15.5	16.5
TICC2538	Texas Instruments	2400	250	1.3	24	20
TICC2531	Texas Instruments	2400	250	.4	29	20.5

3.2. Computing Subsystem

The central component of sensor node is Computing Subsystem which is used to allow management and data processing in the sensor node. Micro-Controller Unit (MCU)is usually implements the Computing Subsystem, which is consist of a micro-processor, memories, Analog-to-Digital Converter (ADC), configurable I/O ports, timers, and other peripherals[16-19]. Energy consumed in a computing subsystem can be expressed as

$$E_{comp} = E_{pro} + E_{logg}$$

Where E_{pro} is the total energy dissipation by MCU used for data processing/aggregation b bit packet and E_{logg} is consumes energy used for reading b bit packet data and writing it into memory. E_{pro} and E_{logg} can be expressed as [11], [23] :

$$E_{pro} = bN_{cyc}C_{avg}V^2{}_{sup} + bV_{sup}\left(I_o e^{\frac{V_{sup}}{n_p V_t}}\right)(\frac{N_{cyc}}{f})$$

$$E_{logg} = E_{write} + E_{read} = \frac{bV_{sup}}{8}(I_{write}T_{write} + I_{read}T_{read})$$

Where V_{sup} is the supply voltage, N_{cyc} is the number of clock cycles per task, C_{avg} is the average capacitance switched per cycle, I_o is the leakage current, n_p is the constant which depends on the processor, V_t is the thermal voltage, f is sensor frequency, E_{write} is energy consumption for writing data, E_{read} is energy consumption for reading b bit packet data, I_{write} and I_{read} are current for writing and reading 1 byte data, and T_{write} and T_{read} are Time for writing and reading 1 byte data. The Features of MCUs from several manufacturers are given in Table 2 [16-19].

3.3. Sensing Subsystem

There are wide ranges of low power sensors appropriate for WSNs. Small sensing time, acceptable accuracy and low power consumption are essential requirements for sensing. The energy consumption per unit time in sensing unit at sensor node can be express as [20].

$$E_{Sensing} = \frac{T_{sense}}{T} bV_{sub}I_{sense}$$

where I_{sense} is the total current required for sensing activity, T_{sense} is the sensing time, T is the sensing period, and b is the number of bit which generate at each activity. The features of some low power sensors are given in Table 3[16-21]

Table2.The Comparison of Features of Low Power MCUs

Name	Manufacturer	SRAM (kB)	FLASH (kB)	1MIPS (mA)	Sleep (μA)
AT89C51RE2 (8051)	Atmel	8	128	7.4	75
ATmega103L (AVR)	Atmel	4	128	1.38	1
CY8C29666	Cypress	2	32	10	5
M68HC08	Freescale	2	61	3.75	22
PIC18LF8722	Microchip	3.9	128	1.0	2.32
PIC24FJ128	Microchip	8	128	1.6	21
XE8802 (CoolRisc)	Semtech	1	22	0.3	1.9
MSP430F1611	Texas Instruments	10	48	0.33	1.3

Table 3. Features of Typical Sensors

Name	Type	Sensing time	Active current
SLG64-0075	Liquid-Flow	30ms	5.1mA
SFM4100	Gases- Flow	4.6ms	12.5mA
VTISCA3000	Acceleration	10ms	120μA
VTISCP1000	Airpressure	110ms	25μA
SensorionSHT15	Humidity	210ms	300μA
AvagoAPDS-9002	Illumination	1.0ms	2.0mA
HitachiHM55B	Magneticfield	30ms	9.0mA
FastraxiTRAX03	Position	4.0s	32mA
DallasDS620U	Temperature	200ms	800μA

3.4. Power Subsystem

The power subsystem stores energy in battery and supply suitable voltage levels. It consists of battery and a voltage regulator[22]. The energy consumed in the power subsystem can be express as

$$E_{pow} = (V_{in} - V_{out}) \times I_{out} \times T$$

Where V_{in} and， V_{out} are the input voltage and output voltage respectively, I_{out} output Current and T is Operate time.

Some time, harvesting units are appended to power subsystem. Due to nature and environment, energy harvesting units don't provide a constant power rate. So, these units are mainly worked in combination with a storage device such as a rechargeable battery or super-capacitor. Storage device stores additional energy and offers it later, when there is no energy can be harvested from the environment. We listed below some common scavenging sources which are used in WSNs[23] and the typical amount of power made by diverse energy sources is summarized in Table 4 [19].

- **Solar cells** use light of sun to produce electricity and it are very common energy harvesting sources. Small panel supplies sufficient power to sensor node. A rechargeable battery or a super-capacitor is usually used with solar cells.
- **Small- scale wind mills** are unusually energy harvesting sources and it appropriate for outdoor applications.
- **Radiant energy** is harvesting technique that convert energy from electromagnetic waves.
- **Vibration energy** is harvesting method that convert vibration energy. It common uses with civil engineering applications.
- **Thermal energy** is harvesting technique that convert the temperature difference between two materials to energy. here are a wide

Table 4. Typical Amount of Power Made by Diverse Energy Scavenging

Energy Source	Duration	Power Density
Temperature Difference	$40\mu W/cm^3/5°C$	Continuous
Piezoelectric	$200\ \mu W/cm^3$	Operation (e.g button push)
Air Flow	$380\mu W/cm^3/5\ m/s$	Continuous
Solar cell	$15\ mW/cm^2$	Continuous

4. Communication Protocols Stack

In WSNs, there are five communication layers: physical layer, data link layer, network layer, transport layer, and application layer as shown in Figure 2[24]. Each layer in the communication protocol stack has its own parameters which effect on the energy consumption in this layer as shown in Figure 3. In the following, we discuss the most relevant features of each communication layer and its impact on energy consumption.

4.1. Physical Layer

Physical layer is the lower layer of the communication layers and it provides the interface to the sensor node to communicate with other node over the physical medium. The function of physical layer is carrier frequency generation, modulation, and signal detection. In WSNs, the physical layer should be given a special care due to the characteristic constraints, such as low-power consumption and hardware design , such as low-power consumption and hardware design [24-25].
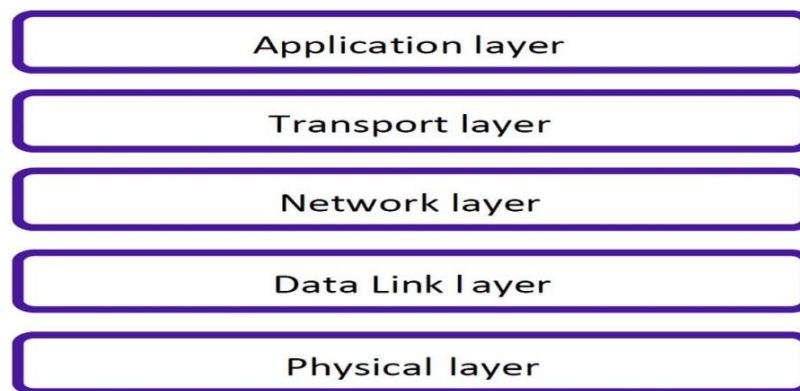

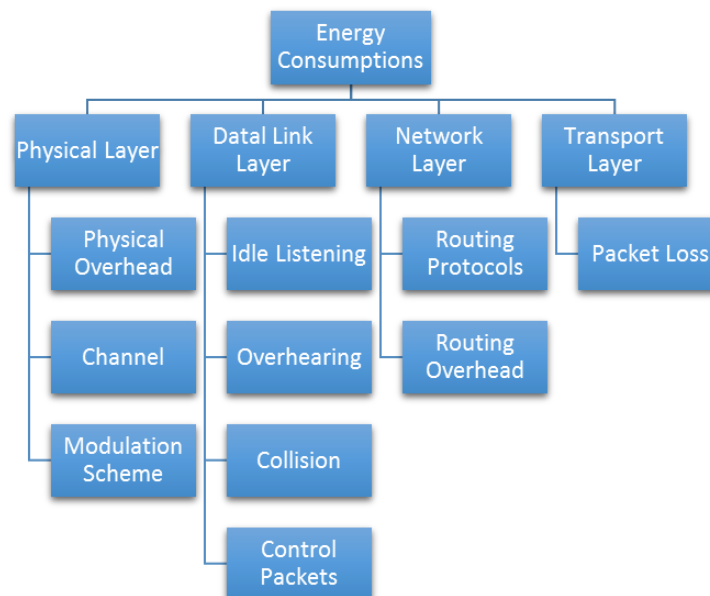**Figure 2 . Architecture of a WSN Communication Protocol**

Figure 3. Energy consumption parameters in WSNs

In physical layer, processing unit has two low-Power techniques for saving energy; DVS (Dynamic Voltage Scaling) and DMS (Dynamic Modulation Scaling. DVS technique based on varying computation load with time, and highest system performance

is not continually necessary. Actually, this technique is used for reducing CPU energy consumption by dynamically changing the supply voltage and clock speed based on the instantaneous amount of work. Similarly in DMS, the modulation level can be adjust in accord with the instantaneous communication load [4].

4.2. Data link Layer

The second layer of the communication stack is Data link layer (DLL) and it generally consists of two sub-layers: Logical Link Control (LLC) and Medium Access Control (MAC). The functions of MAC protocols are providing connections for the routing protocol and managing transceiver unit on a shared wireless medium. In general, there are two categories of MAC protocols [25].

1) Schedule-based Protocols which is depend on scheduling and reservation. Time-division multiple access (TDMA) is a good example of these type of protocols, in which the time is divided into several time slots. Each time slot is assigned to a sensor node and a node can transfer message during its assigned time.

2) Contention-Based MAC Protocols, in which nodes compete to reserve shared wireless media and trying to avoid packet collisions. In this type of MAC protocols, duty cycling is used to advanced energy saving, where the time is divided into a long sleep period and a small active period. This type of MAC protocols can be classified, according to the synchronization of data exchanged, into two categories: unsynchronized and synchronized protocols [26, 27].

MAC protocols have a very high effect on network performance and energy consumption. Therefore, a MAC protocol should minimize [19]:

• **Idle listening**: Idle listening happens when a node is actively receiving a channel, but there is no significative action on the channel resulting loss of energy[28].

• **Collisions:** Collisions occurs when two or more nodes transmit simultaneously at the same channel Thus, the received packet is presumably corrupted producing unusable receive fee at the destination node and unusable transmit fee at the source node.

• **Overhearing**: Overhearing occurs when node receives packets that are sent to the shared medium and they are not destined for it and consumes unnecessarily energy.

• **Protocol overhead**: In WSN system, short packets, protocol headers and trailers are used, which causing significant energy consumption. Moreover, the energy consumption due to control packet exchange, such as ACK packet may be very significant.

Therefore, energy consumed in the sensor node with take in to account MAC layer can express as

$$E_{mac} = E_{hw} + E_{ohear} + E_{ohead} + E_{retx} + E_{idle}$$

where E_{ohear} and E_{ohead} are the energy consumed due to overhearing and overhead, respectively, E_{retx} is the energy consumed due to retransmitted losses packets, which is resulting from collisions, and E_{idle} is wasted energy in idle state.

4.3. Network Layer

The third layer in the WSNs communication protocol stack is the network layer. The functions of network layer are network routing, error control, source to destination packet delivery, network segmentation and de-segmentation, and flow control. In WSNs, finding the route between a source node and destination node is task of the routing protocols. Based on the operation of WSNs routing protocols, it can be categorized into: node-centric, data-centric, location based, multipath routing, hierarchical protocols, mobility-based protocols, and QoS-based protocols [29, 30]. At the network layer, routing

protocols have a very high effect on network performance and energy consumption. Thus, it had better take into account the following goals in to decreasethe energy consumption and extend lifetime [25].

• Minimization of the Energy Consumed per bit or Packet.

The energy consumed per bit or Packet is the energy that is used for the transmission of the bit/Packet from the source to the sink.

• Maximization of the Network lifetime.

The network lifetime is the duration time before the network loses its connectivity.

• Minimization of the Budget per Packet and Node.

The budget per packet is defined as the energy consumed for transfer a packet from the source node to the sink node over the shortest route. The objective is to reduce the budget per packet, which can be reached by avoiding those sensor nodes with the smallestremaining energy on selected routes. Also, the budget per node is defined as the amount of energy consumed by each senor node for transferring a packet to the sink node. This objective is to reduce the budget per node with the aim of the lifetime is maximized.

4.4. Transport layer

The fourth layer in the WSN communication protocol stack is the transport layer. It provides services such as flow control, multiplexing and reliability between end users.The purpose of this layer is to provide reliable data transfer between source and destination, thus relieving the upper layers' responsibility for providing reliable and cost-effective data transfer [22].

In the context of WSNs, not much work has been done to address the energy consumption issue at the transport layer. But it is easy to find out its effect on the energy consumed. Where it is at calculating the energy consumed in sensor node a new term $E_{retrspos}$ appears in the equation as a result of re-transmitter in Transport layer.

4.5. Application layer

The last layer of the WSN communication protocol stack is the application layer and it makes common services for the application. The Sensor Management Protocol (SMP), and the Sensor Query and Data Dissemination Protocol (SQDDP) are examples of application protocols in WSNs [3], [16].

5. Energy Consumption Models

The energy consumption model may be defined as designing and analyzing a mathematical representation of a WSN to study the effect of changing the system parameters. The behavior of energy consumption model is a function of its parameters. The parameters may be set when design time, in which case they may be considered as fixed resources (*e.g.,* Initial energy), or they may change after a system has been implemented (*e.g.,* Packet sizes and transmitted power).

There are several previous attempts to model energy consumption for sensor node. In general energy consumption models can be classified into three categories, physical layer energy models, MAC layer energy models and cross-layer energy models. Physical layer energy models are models that take into account the parameters of energy consumption at physical layer only .This include transmitted power, received power and sensing power. MAC layer energy models are models that take into account the parameters of energy consumption at physical layer and parameters of energy consumption at MAC layer .This include overhead of MAC protocol, overhearing and collision. Cross-layer energy models

are models that take into account parameters of energy consumption at various communication layers [31]. We summarized energy consumption parameters that are considered by various energy models in Table [5].

Table 5. Energy Consumption Parameters Considered in Various Energy Models

	Transmit ted power	TX circuit power	RX circuit Power	Processi ng power	Sensin g power	Overhead
[32]	√	-	√	-	-	-
[33]	√	-	√	-	-	-
[34]	√	-	√	-	-	-
[7]	√	-	√	-	-	√
[35]	√	√	√	√	-	-
[36]	√	√	√	-	-	-
[37]	√	√	√	-	-	-
[38]	√	-	√	-	√	-
[39]	√	√	√	-	√	-
[40]	√	-	√	-	√	-

6. Conclusions and Future Work

Energy consumption in WSNs is extremely important due to limitation of power sources. In this paper, an overview of WSNs constrains and judgment metrics such as lifetime and latency are given. Moreover, we have given an introduction to source of energy consumption at each layer. Then, surveys have been provided for existing energy models. These models are classified into physical layer, MAC layer and cross-layer energy models. However, as the energy-awareness must be incorporated into all aspects of system hierarchy, there are still many open issues for future research. Future work will include, providing a new energy model which capture all energy consumption sources in all communication layers stack.

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