Survey on Energy Consumption Models in Wireless Sensor Networks

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Abstract:

Wireless Sensor Network (WSN) is one of the most important areas of research in the twenty-first century. WSN aims to sense a certain natural phenomenon and sends sensed data to sink using a multi-hop network. In order to increase the lifetime of the battery-based sensing nodes, it is essential to minimize the consumed energy in the sensing process. The first step to achieve this goal is to know completely the sources of energy consumption in WSNs. In this paper, sources of energy consumption at various communication layers have been studied and investigated. Furthermore, survey has been provided for existing energy models and the classification of these models into physical layer, MAC layer and cross-layer energy models. Finally, a comparison between existing available energy models has been provided.

Keywords:

Energy Consumption Models; Wireless Sensor Networks; ad hoc Networks; Networking Layer; Data Link Layer; Medium Access Control; Physical Layer; Cross-layer

1. INTRODUCTION

WSNs have been widely considered as one of the most important technologies for the twenty first century. Typically WSN 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, 2]. WSNs have gained worldwide attention in recent years, particularly with the proliferation in Micro-Electro-Mechanical Systems (MEMS) technology which has facilitated the development of smart sensors [3]. The features of WSNs enable monitoring, object tracking, and control functionality [4]. WSNs are systems that are subjected to severe energy consumption constraints and extending sensor node battery life is a paramount requirement for network autonomy. A better understanding of where energy is spent in a typical wireless sensor node is a first step towards achieving this goal.

There are several metrics used to judge the quality of a WSNs. Some of these include network Lifetime (LT) which is a significant metric depending on many factors, including network architecture and protocols, data collection initiation, lifetime definition, channel characteristics, and energy consumption model [5], Energy Efficiency (EE) which aimed to reduce the amount of energy usage for a given task (e.g. Energy efficient clustering scheme (EECS) [6]), Energy-Per-Useful-Bit (EPUB) which captures overhead due to physical layer modulation [7], end-to-end latency which refers to the time taken for a packet to be...
transmitted across a network from source to destination [8], and Expected Data Rate (EDR) that captures
the effect of per-hop contention on multi-hop throughput [9].

The network lifetime becomes a critical metric in the design of WSNs. While various solution
techniques have been proposed to maximize the network lifetime. Some of these include energy-aware
MAC protocols, power aware storage, routing and data dissemination protocols, duty-cycling strategies,
adaptive sensing rate, tiered system architectures, and redundant placement of nodes [10]. The former of
lifetime is sometime hard to compute, because of the randomness of behavior of radio access procedures
and the unknown number of re-transmission need to overcome problems due to packet collisions and
channel error, etc. [11]. As we mentioned above that the network lifetime depends on the definition, so
we listed below some definitions of network lifetime which were used in previous work:

**Definition 1.**
Network lifetime is defined as the period from the start of the network operation to the moment when the first sensor
in the network runs out of energy [12, 13].

**Definition 2.**
Network lifetime is the maximal time beyond which the desired network performance cannot be achieved [14].

**Definition 3.**
Network lifetime is defined as the time interval during which the end-to-end data rate is maintained above a minimum
required rate [15].

**Definition 4.**
Network lifetime can be defined as the interval of time, starting with the first transmission in the wireless network
and ending when the percentage of node that have not terminated their residual energy falls below specific threshold,
which is set according to the type of application [5].

**Definition 5.**
Network Lifetime is defined as the time duration within which the desired signal-to-noise ratio (SNR) at the destina-
tion is met with a certain probability [16].

The functionality of a sensing node is generally implemented through four units which are; sensing,
processing, communication and power units [1, 2, 17–19] as shown Fig.1. Each unit has three states; active,
idle and sleep [20]. Power-consuming in each unit depends on the state of the unit. The communication
system, utilized to transmit information between the nodes [21], is a major functional block in every WSN.
Practical communication system design is aided by the communication protocol stack. That is made
up of a physical layer, data link layer, network layer, transport layer and application layer as shown in
Fig.2, where each layer is responsible for specific sub-systems. Each layer in the communication protocol
stack has its own parameters which effect on the energy consumption in this layer as shown Fig.3. The
functions and the power consumption sources of each layer are described as follows [2, 22]:

1. Physical (PHY) layer: PHY layer focuses on the transmission of bits reliably over a point-to-point
wireless link. The major functions performed by this layer are modulation, coding, diversity and
power control. In PHY layer, there is energy consumption in hardware of WSN node (sensor,
processor, transceiver and power unit), wireless channel error, modulation scheme (e.g. QPSK) and
physical layer overhead.

2. Medium Access Control (MAC) layer: MAC layer controls how different users share the given
spectrum. The spectrum allocation can be performed through either deterministic or random
access. In MAC layer, sources of energy consumption depend on type of MAC protocol (Schedule based or Contention based), overhead of MAC protocol, overhearing and collision.

3. Network layer: This layer provides the means of transferring data sequences from a source to a destination. This layer performs network routing and dynamic resource allocation. In network layer, energy consumption is affected by the type of routing overhead protocol.

4. Transport layer: This layer usually responsible for end-to-end error recovery and flow control and for ensuring complete data transfer. In transport layer, packet loss between source and destination lead to increased energy consumption.

5. Application layer: It generates data to be sent over the network and processes the data received over the network. Source coding is the main function of the application layer. Energy consumption in this layer mainly depends on the application type.

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) [23]. There are several previous attempts to model energy consumption for sensor node. We summarized common energy consumption parameters that are considered by various energy models in Table (1).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitted power ($P_{ti}$)</td>
<td>It is the energy consumption per second for transmitting one unit of data from node $i$ to node $j$. This parameter is used in most of models such as those developed in [7, 12, 24–32].</td>
</tr>
<tr>
<td>Received power ($P_{ri}$)</td>
<td>It is the energy consumption per second for receiving one unit of data from node $i$ to node $j$ [7, 12, 24–32].</td>
</tr>
<tr>
<td>Energy for sensing ($e_s$)</td>
<td>It is the energy consumption for sensing one bit [31–32].</td>
</tr>
<tr>
<td>Link data rate ($R_{ij}$)</td>
<td>It is the average flow of traffic (bits per second) from node $i$ to node $j$ [26, 30, 33].</td>
</tr>
<tr>
<td>Physical layer overhead ($B_P$)</td>
<td>It is the redundancy bits in packet at physical layer [7].</td>
</tr>
<tr>
<td>Overhearing</td>
<td>It occurs when node receives packets that are sent to the shared medium and they are not destined for it [33, 34].</td>
</tr>
<tr>
<td>Collision</td>
<td>It occurs when two nodes transmit at the same time [34].</td>
</tr>
<tr>
<td>MAC layer Overhead</td>
<td>It is the overhead at MAC layer which depend on type of MAC protocol, e.g. ACK, RTS and CTS [34–37].</td>
</tr>
<tr>
<td>Sleeping power ($P_{sleep}$)</td>
<td>It is the power wasted when a sensor node turns off all units [34–37].</td>
</tr>
<tr>
<td>Transient power ($P_{trans}$)</td>
<td>It is the power wasted when node changes its operating mode [35].</td>
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In this paper, a survey of existing energy models has been provided. These models have been classified into 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. This paper provides also a comparison between existing available energy models has been provided.

The rest of the paper is organized as follows. Section 2, is dedicated to energy consumption models at physical layer. Section 3, discusses the energy consumption models at physical layer and data link-layer. Section 4, discusses energy consumption models at cross-layer. Finally section 5, concludes the paper and investigates possible future work directions.

## 2. PHYSICAL LAYER ENERGY CONSUMPTION MODEL

The physical layer provides an interface to transmit a stream of bits over physical medium. It is responsible for frequency selection, carrier frequency generation, signals detection, modulation and data encryption [2]. Several researchers have examined the energy consumption model in physical layer [7, 12, 24–32]. Some of these models consider the energy consumption due to transmitting and receiving sensory data such as those developed in [12, 24–26]. In [24], authors provide a first effort on network
lifetime maximization that consider the general optimization problem in which all the three layers of routing, power control, and random link access are considered jointly. They also provide an analytical model for energy consumption in WSNs. WSN is modeled as a directed graph $G_1 = (V, L)$, where $V$ includes $N$ sensing nodes and one sink node, and $L$ denotes the directed link set; $(i, j) \in L$ means that sensor node $i$ can transmit data to sensor node $j$. For each sensor node $i$, associate a routing variable $x_{ij}$ with each link $(i, j) \in L$. $x_{ij} > 0$ means that the link $(i, j)$ is selected by sensor node $i$ to forward messages to sensor node $j$, and $x_{ij} = 0$ means that the link $(i, j)$ is not selected. The power consumption rate at the $i^{th}$ sensor node $i$, $P_i$ is equal to

$$P_i = \sum_{j \in (i,j) \in L} x_{ij}p_{ij} + \sum_{j : (j,i) \in L} x_{ji}p_{ji}'$$

(1)

where $p_{ij}$ and $p_{ji}'$ denote the energy consumption per second for transmitting and receiving one unit of data over link $(i, j)$ respectively. Similarly in [12], the maximum lifetime routing problem is extended to include the energy consumption at receivers during reception. The authors provide energy consumption at node $i$ which is given by

$$E_i = \sum_{j \in S_i} e_{ij}^{'} \sum_{c} q_{ij}^{(c)} + \sum_{j \in S_i} e_{ji}' \sum_{c} q_{ji}^{(c)}$$

(2)

where $e_{ij}^{'}$ and $e_{ji}'$ denote the energy consumption at node $i$ for transmitting and receiving a data unit to its neighboring node $j$ respectively, $q_{ij}^{(c)}$ is the transmission rate of commodity $c$ from node $i$ to node $j$ and $S_i$ is the set of all nodes that can be directly reached by node $i$ with a certain transmit power level in its dynamic range. $C$ is the commodity which is defined by a set of source nodes and destination nodes.
In [25], the authors exploit sink mobility to prolong the network lifetime in wireless sensor networks where the information delay caused by moving the sink should be bounded. They also addressed the problem of lifetime maximization with delay bound in a mobile WSN. WSN modeled as a graph $G_2 = \{v \cup v_0, \mathcal{L} \cup \mathcal{L}_0\}$, where $v$ and $v_0$ is the set of sensors and sink sites respectively, $\mathcal{L} \subseteq \{v \times v\}$ is the set of wireless links between sensors, $l_{ij} \in \mathcal{L}$ if sensor $j$ is within the communication range of sensor $i$. Similarly, $\mathcal{L}_0 \subseteq \{v \times v_0\}$ is the set of links between sensors and sink sites. So energy consumption at node $i$ is calculated as follows:

$$E_i = e_{ij}^l \left( \sum_{l_{ij} \in \mathcal{L}} f_{ij} \right) + e_{ik}^l \left( \sum_{l_{ik} \in \mathcal{L}_0} f_{ik} \right) + e^R \left( \sum_{l_{ijk} \in \mathcal{L}} f_{ji} \right) \tag{3}$$

where $e^R$ denotes the energy cost for receiving one unit data and $f_{ij(k)}$ (in bits) is the amount of data transmitted from node $i$ to $j$ ($s_0$ in site $k$).

In [26], energy consumption is reduced by minimizing the data flow through each link while satisfying the information generation rate of each node. Authors showed that the amount of traffic present in the link at a given time affects the energy consumption. They assumed WSN with $Z$ sensor nodes and show that the total energy consumed at node $i$ to transmit and receive data is given by

$$E_i = \sum_{i,j \in Z} p_j R_{ij} + \left( p_j^r + \varepsilon_{\text{amp}} d_{ij}^2 \right) c_{ji} R_{ij} \tag{4}$$

where $R_{ij}$ is the average flow of traffic (bits per second) on a link $(i, j)$, $\varepsilon_{\text{amp}}$ is the transmitter amplification coefficient of the transmitter, $d_{ij}$ The distance for link $(i, j)$, and $c_{ji}$ is the indicator function of the condition that node belongs to link $(i, j)$.

In [7], the concept of Energy-per-Useful-Bit (EPUB) metric was introduced for evaluating and comparing sensor network physical layers. This metric aimed to define a way of computing the energy consumption. The feature of this energy model includes the energy consumption of both the transmitter and receiver, and amortizes the energy consumption during the synchronization preamble over the number of data bits in the packet. The authors define the EPUB metric as:

$$\text{EPUB} = \left( \frac{B_D + B_P}{B_D} \right) (P_{TX} + \xi P_{RX}) T \tag{5}$$

where $B_D$ and $B_P$ are respectively the average number of data and preamble bits in a packet, $T$ is the bit time in seconds. $P_{TX}$ is the power of the transmitter in W, and $P_{RX}$ is the power of the receiver in W including the analog-to-digital converter and synchronization circuitry. The constant $\xi$ is determined by the MAC scheme and represents the average proportion of time spent in receive mode divided by that spent in transmit mode. By investigating this equation we can see that authors take into consideration the transmitting power, receiving power including analog circuit, and preamble bits. In the other side, they discarded other sources of energy consumption including like sensing power, signal processing power, power loss due to channel estimation and feedback loss.

Some other energy models not only consider the energy consumption due to transmitting and receiving sensory data but also consider over-heads of transmitter electronics and overhead of receiver electronics such as those developed in [27–29]. In [27], coordination and communication problems in Wireless Sensor and Actor Networks (WSANs) are jointly addressed in a unifying framework. The authors introduced model for energy consumption per bit at physical layer and it is given by:
\[ E_b = E_{\text{elec}}^{\text{trans}} + \beta d^\alpha + E_{\text{elec}}^{\text{rec}} \]  

where \( E_{\text{elec}}^{\text{trans}} \) is a distance-independent term that takes into account over-heads of transmitter electronics (phase-locked loops, voltage-controlled oscillators, bias currents, and so forth) and digital processing, \( E_{\text{elec}}^{\text{rec}} \) is a distance-independent term that takes into account the overhead of receiver electronics, and \( \beta d^\alpha \) is a distance-dependent term that accounts for the radiated power necessary to transmit one bit over a distance \( d \) between the source and the destination where \( \alpha \) is path loss \((2 \leq \alpha \leq 5)\) and \( \beta \) is constant [\text{J/bit.m}^{\alpha}]\).

In [28], proposed an energy consumption model for radio transceivers, designed especially for WSNs. The main issue discussed is how to estimate the energy needed to send a package of \( n \) bits of data from the transmitter to the receiver, as shown in Fig.4.

\[ E_{TX}(n,d) = E_{ic}(n) + E_{amp}(n,d) = n.E_{\text{trans}} + n.\varepsilon_{\text{amp}}.d^\alpha \]  

where \( E_{ic}(n) \) is the energy that the radio circuit needs to consume in order to process \( n \) bits, \( E_{amp}(n,d) \) is the energy needed by the radio amplifier circuit to send \( n \) bits \( d \) meters, \( E_{\text{trans}} \) is the energy needed to process a single bit by the radio transmission circuits and \( \varepsilon_{\text{amp}} \) is the transceiver’s energy dissipation which can be expressed as

\[ \varepsilon_{\text{amp}} = \frac{S}{N_0}.N_{\text{FXR}}.N_0.BW.(\frac{4\pi}{\lambda})^2}{G_{\text{ant}}.\eta.R_{\text{bit}}} \]  

where \( S \) is the signal to noise ratio at the receiver, \( N_{\text{FXR}} \) is the receiver noise figure, \( N_0 \) is the noise power spectral density, \( BW \) is the channel noise bandwidth, \( \lambda \) is the wavelength in meters, \( G_{\text{ant}} \) is the antenna gain, \( \eta \) is the transmitter efficiency and \( R_{\text{bit}} \) is the channel data rate in bits per second.

In [29], simple power consumption models for major components are individually identified, and the effective transmission range of a sensor node is modeled by the output power of the transmitting power amplifier, sensitivity of the receiving low noise amplifier, and RF environment.

The authors developed a realistic power consumption model for WSN devices by incorporating the characteristics of a typical low power transceiver. Fig.5 illustrates the internal structure of a communication module found in a typical WSN node. The total power consumption for transmitting and for receiving, denoted by \( P_T(d) \) and \( P_R \) are given by equations (9) and (10).
$P_T (d) = P_{TB} + P_{TRF} + P_A (d) = P_{TB} + P_{TRF} + \frac{P_{RX} \times A \times d^\alpha}{\eta}$ \hspace{1cm} (9)

where

$P_A (d) = \frac{P_{RX} \times A \times d^\alpha}{\eta}$ \hspace{1cm} (10)

$P_R = P_{RB} + P_{RRF} + P_L$ \hspace{1cm} (11)

where $P_A (d)$ is the power consumption of the power amplifier which is a function of the transmission range $d$, $P_{TB}$ and $P_{RB}$ are the power consumption in baseband DSP circuit for transmitting or receiving, $P_{TRF}$ and $P_{RRF}$ are the power consumption in front-end circuit for transmitting or receiving, $P_L$ is the power consumption of LNA for receiving, and $A$ is determined by the characteristics of the transmitting and receiving antennas.

Figure 5. Communication Module Structure

Finally, some of the energy models consider the energy consumption due to transmitting and receiving sensory data as well the energy consumption due to sensing [30–32]. In [30], the authors discussed the sufficient condition on link bandwidth that makes a routing solution feasible, then provided mathematical optimization models to tackle both energy and bandwidth constraints. They showed that ignoring the bandwidth constraint can lead to infeasible routing solutions. They assumed that a WSN has $n$ nodes and each node $i$ generates sensory data at a rate of $R_i$ bits per second ($R_i > 0$ if node $i$ is a source, $R_i = 0$ if it is a pure relay node, and $R_i < 0$ if it is a sink), $e_s$ is energy consumption coefficients for sensing one bit and $N_i$ denote the neighbors of $i$ excluding $i$ itself. Then the total energy consumed per second in a node $i$ can be expressed as

$P_i = e_s R_i + \sum_{j \in N_i} (P^s_{ij} R_{ji} + P^t_{ij} R_{ij})$ \hspace{1cm} (12)

In [31], The objective of the authors is investigate how the network lifetime is affected by link conditions such as the maximum transmission power of a node and the peak data rate of a link. They considered an ad hoc network consisted of nodes that transmit data and signaling packets asynchronously employing direct sequence spread spectrum (DSSS) waveforms. A node $i$ having a packet to send to node $j$ transmits it at a given instant with a given probability $\varphi_{ij}$. In other words, $\varphi_{ij} \geq 0$ denotes the average fraction of
time in the routing (scheduling) interval $T$ that node $i$ transmits to node $j$. Then the total energy consumed per second in a node $i$ is

$$P_i = \sum_{j \neq i} \phi_{ij} (P_t + p_{ij}) + \sum_{j \neq i} \phi_{ji} P_r + P_c$$  \hspace{1cm} (13)$$

where $P_c$ denotes the power consumption of the node without transceiver, $P_t$ is the power consumed by the baseband part of the transmitter and $P_r$ denotes the power consumption of the receiver. $p_{ij}$ is fixed power when node $i$ transmits to node $j$.

In [33], the authors jointly considered congestion control, routing and time slots allocation to study the tradeoff between utility and lifetime in energy-constrained WSNs. They considered a WSN that consists of a set of sensor nodes indexed from 1 to $N$ and a sink that collects data from these nodes. Then the total average power dissipated in the node $i$ is given by

$$P_i = \sum_{l \in L_{out}(i)} f_i + \sum_{l \in L_{in}(i)} f_i + e_i R_i$$  \hspace{1cm} (14)$$

where $L_{out}(i)$ denoted the set of outgoing links from node $i$, $L_{in}(i)$ the set of incoming links to node $v$. $f_i$ is the average amount of flow destined to the sink in link $l$.

In [32], the authors addressed a new problem in which the network cost is minimized (by optimizing the number and locations of sensors) while the resulting lifetime is at least equal to a given value. They considered surveillance network consists of a base station and some sensors, where the base station is located at a given position while the number and locations of sensors are to be optimized. The sensors are used to: 1) monitor the given targets located at fixed positions (e.g., the targets are the precious items located at fixed positions in an exhibition), 2) collect the sensed data, and 3) transmit this data to the base station. Then the energy usage for transmitting one bit at node $i$ is given by

$$E_i = e_T + e_i + \beta (d_{max} + R_s)^\alpha$$  \hspace{1cm} (15)$$

where $e_T$ is the energy usage per bit of the transmitter electronics, $R_s$ is the sensing range of each sensor, and $d_{max}$ is the maximum distance between any target. We summarized energy consumption parameters that are considered by various energy models in Table 2.
3. PHYSICAL LAYER AND DATA LINK LAYER ENERGY CONSUMPTION MODEL

Data link layer (DLL) is mainly divided into two sub-layers: Logical Link Control (LLC) and Medium Access Control (MAC) sub-layer. In the following, we will only address the MAC sub-layer, since it has more significant effects in terms of energy-consumption and real-time issues. The MAC sub layer is the lowest part of the data link layer and it operates on top of the physical layer. The MAC protocol manages radio transmission and reception on a shared wireless medium and provides connection for overlying routing protocol, so it has a very high effect on network performance and energy consumption [38]. Some work joint physical layer and data link layer is reported [35–37, 39, 40].

In [35], The authors endeavors to jointly optimize energy-efficient routing that balances traffic load across the network according to energy-related metrics and sleep scheduling that reduces energy cost due to idle listening by providing periodic sleep cycles for sensor nodes to maximize overall network lifetime. They give formulate of average energy consumption for specific MAC protocol. In which sending multiple short preambles till one is heard by the receiver (e.g., TICER) as shown in Fig.6.

They compute the energy consumptions of a node during an active period, which could be an idle listening slot, a data transmission slot, or a data receiving slot. In the data transmission slot, the average energy consumption for node $i$ to transmit one packet to node $j$ is given by

$$E_{tx}^{ij} = \left( E_{rf} + p_{rx} T_{det} \right) - E_{rf} + \left( E_{rx} + \left( p_{tx} + p_{rx} \right) T_{pre} \right) \times \left( \frac{T_{j}^{tx}}{2} - \frac{2T_{pre} + T_{sav} + T_{rf} + 2T_{pre}}{T_{rf} + 2T_{pre} T_{sav}} \right) + p_{tx} T_{data} + p_{rx} T_{pre}$$

(16)

where $E_{rf}$ is the amount of energy to initialize its RF circuits, $p_{tx}$ is the transmitted power level, $p_{rx}$ is the received power level, $T_{pre}$ is the duration time of RTS, CTS, and ACK packets, $T_{rf}$ is the initialization period duration of the circuits, $T_{j}^{tx}$ is the sleep period time, $T_{sav}$ is the time for power saving status when resend (RTS) preamble, $T_{data}$ is the duration of a data packet, and $T_{rf}$ is equal to the shortest
allowable duration, i.e., $T_{\text{det}} = 2T_{rf} + 3T_{\text{pre}} + T_{\text{sav}}$. Hence, the term \( \frac{T_{\text{j slp}}}{2} - \frac{(2T_{\text{pre}} + T_{\text{sav}} + T_{rf} + 2T_{\text{pre}})}{T_{rf} + 2T_{\text{pre}} + T_{\text{sav}}} + 2 \) denotes average number of RTS preambles the transmitter has to transmit until one is captured by node $j$. Furthermore, the energy consumption for a node to receive a packet $E_{\text{rx}}$ and the energy cost due to idle listening $E_{\text{det}}$ are given respectively by

\[
E_{\text{rx}} = \left( E_{rf} + p_{rx} \frac{T_{\text{det}}}{2} \right) + p_{rx} T_{\text{data}} + 2p_{rx} T_{\text{pre}} \tag{17}
\]

\[
E_{\text{det}} = E_{rf} + p_{rx} (T_{\text{det}} - T_{rf}) \tag{18}
\]

In [35], the average power consumption is calculated as

\[
p_i = \sum_{j \in N_i} E_{ij} R_{ij} + E_{\text{rx}} \sum_{j \in N_i} R_{ji} + \frac{E_{\text{det}}}{T_{\text{det}} + T_{\text{j slp}}} \tag{19}
\]

where $R_{ij}$ is the average rate at which node $i$ transmits packets to node $j$, and $R_{ji}$ is the average rate at which node $i$ receives packets from other nodes. By investigating this equation we can see that authors write formulation considers a more realistic power consumption model which includes energy costs due to payload transmission and reception, preamble transmission, as well as idle listening. On the other hand this model is designed for specific MAC protocols and other sources of energy consumption in node like overhearing and collision are discarded.

In [36], the authors proposed a new approach to low power listening called X-MAC, which employs a short preamble to further reduce energy consumption and to reduce latency. They developed the average energy consumption for X-MACs short preamble approach. Based on the cycle shown in Fig.7, and assuming uncorrelated packet arrivals and sleep/wake periods, the expected energy to send a packet is given by

\[
E_s = \left( \text{preamble energy} + \text{energy per ACK listen} \right) \times \text{(expected preamble listen iterations required)} + \text{(energy to send packet)} = \left( p_{TX} S_p + p_{RX} S_{al} \right) \left( \frac{1}{R_1 - S_p} \right) + S_d P_{TX} \tag{20}
\]

where $S_p$, $S_{al}$, and $S_d$ denote the duration of the sender’s preamble, acknowledgment listen, and data transmission periods, respectively. $R_1$ and $R_e$ denote the receiver listen and sleep periods. Furthermore, the expected energy to receive a packet is given by

\[
E_r = \left( \text{listen cycle energy} + \text{sleep cycle energy} \right) \times \text{(expected iterations for a preamble to arrive)} + \text{(energy to send an ACK)} + \text{(energy to receive packet)} = \frac{p_{TX} R_s + p_{RX} R_l}{1 - (1 - P_d(t))^R_{1-e} + p_{TX} R_a + R_d P_{RX}} \tag{21}
\]

where $R_d$ and $R_a$ denote the duration of ACK and packet periods.
In [37], the authors introduced a general average power consumption formula \( P \) for MAC protocols and then they apply it to different MAC protocols. This formula is calculated by normalized transmission \( t_{TX} \) and reception \( t_{RX} \) activities and their power consumption as

\[
P = t_{TX} P_{TX} + t_{RX} P_{RX} + (1 - t_{TX} - t_{RX}) P_{slp}
\]  

(22)

where \( P_{slp} \) is the power consumed at sleep state. The normalized activity is determined by dividing the duration of an activity by the interval of the activity resulting in a percentage value of the activity. For an ideal MAC (Ideal-MAC) protocol, all nodes can exchange data and ACK frames without the need of any synchronization or contention mechanism. Nodes can sleep all the time between frame exchanges. Hence, the Ideal-MAC does not cause any idle listening or control frame overhead. The required activity for exchanging one data frame is presented in Fig. 8. Thus, each data transmission and reception is preceded by a radio start-up transient \( t_{ST} \). Thus, \( t_{TX} \) and \( t_{RX} \) for any node when transmit are given by

\[
t_{TX} = \left( t_{ST} + \frac{L_{DATA}}{R} \right) \frac{1}{T_{DATA}}
\]  

(23)

\[
t_{RX} = \left( t_{ST} + \frac{L_{ACK}}{R} \right) \frac{1}{T_{DATA}}
\]  

(24)

where \( R \) is the data rate of a radio, \( L_{DATA} \) and \( L_{ACK} \) are the length of DATA frame and ACK frame, respectively, and \( T_{DATA} \) is data generation interval in the node.

In [39], the authors considered the lifetime maximization routing with network coding in wireless multihop networks. They first showed that lifetime maximization with network coding is different from pure routing, throughput maximization with network coding and energy minimization with network
coding. In this reference, the wireless multi-hop network is modeled as a directed graph $G = (V, L)$, then the total power consumption in node $i$ can be expressed as:

$$ P_i = P_{TX} + P_{RX} + P_i^o $$  \hspace{1cm} (25)$$

where $P_i^o$ the overhearing power cost.

In [40], the authors presented an energy efficient MAC protocol for WSNs that avoids overhearing and reduces contention and delay by asynchronously scheduling the wakeup time of neighboring nodes. They developed a power consumption model for AS-MAC multi-hop networks. According to this model the total energy consumption per second, $E$ includes transmission, reception, listen, sleep, and LPL is express by

$$ E = T_{tx}P_{TX} + T_{rx}P_{TX} + T_{pl}P_{pl} + T_sP_s $$  \hspace{1cm} (26)$$

where $T_{tx}$, $T_{rx}$, $T_{pl}$, $T_s$ and $P_{tx}$, $P_{rx}$, $P_{pl}$, $P_s$ are time fractions and power for transmission, reception, listen, Low-Power-Listening (LPL), and sleep, respectively. We summarized energy consumption metrics considers by various physical layer and data-link layer energy models in Table 3.

<table>
<thead>
<tr>
<th>Transmitted power</th>
<th>Received circuit Power</th>
<th>Transient sleeping power</th>
<th>MAC layer Overhead</th>
<th>Overhearing power</th>
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</thead>
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</table>

4. CROSS LAYER

Some works perform cross-layer analysis by presenting topology, medium access control (MAC) and physical layer energy consumption models that work in unison as [34, 41]. In [41], authors showed that accurate prediction of sensor network lifetime requires an accurate energy consumption model. They improved existing energy models over-estimate life expectancy of a sensor node by $30 - 58\%$. So they provide a comprehensive energy model with fixed configuration network including certain sources of energy consumption that are not included in previous sensor energy models, i.e., transmit energy, sensor sensing, sensor logging and actuation. They considered a WSN with a cluster topology in which sensors are grouped into clusters, and individual sensors sense data and transmit it to cluster heads (CH) using single hops and assume that all sensor nodes use time division multiple access (TDMA). Authors showed that the total energy consumed by a sensor node $E_N (i,j)$ and cluster head $E_{CH} (j)$ during each round can be expressed respectively by:

$$ E_N (i,j) = [bE_{sensN} + bE_{logN} + bE_{elec} + b d_{iCH}^2 E_{fs} + E_{transN}] $$  \hspace{1cm} (27)$$

$$ E_{CH} (j) = [bE_{sensCH} + bE_{logCH} + b_1E_{proCH} \left( \frac{N_s}{K} \right) + h_2 b_1 E_{elec} \left( \frac{N_s}{K} - 1 \right) + h_2 \gamma b_2 E_{elec} + h_2 b_2 (1 + \gamma) E_{elec} + b_2 (1 + \gamma) d_{iBS}^4 E_{mp} + E_{transCH}] $$  \hspace{1cm} (28)$$
where $b$ is the number of bits in every packet, $d_{toCH}$ is the distance between a node and the CH, $E_{fs}$ is the free space fading energy, $E_{sens}$ and $E_{sensCH}$ are energy dissipation per round for sensing activity at the sensor node and CH, respectively. $E_{logg}$ and $E_{loggCH}$ denote sensor logging energy consumption per round for a sensor node and CH, respectively. $E_{trans}$ and $E_{transCH}$ describe the total transient energy dissipation per round for sensing activity at the sensor node and CH, respectively. $E_{elec}$ is the energy dissipated to transmit or receive electronics, $E_{mp}$ is the multi-path fading energy, $E_{proCH}$ is the total energy dissipation for processing and aggregation by the cluster head (CH), $\gamma$ is the number of clusters. $h_2$ is weighting factor, $N_s$ is the total number of sensors, $K$ is the total number of cluster, $b_1$ is the number of bit process by CH, and $b_2$ is the number of bit in packets which transmits by CH. Therefore the total energy consumed by the entire network per round is given by

$$E_{tot} = \sum_{j=1}^{K} \left( E_{CH}(j) + \sum_{i=1}^{N_j} E_N(ij) \right)$$

(29)

where $N_j$ is the number of sensor nodes in each cluster.

In [34], a new analytical model was developed for calculating the energy consumption at each sensor node per unit of time, given a specific routing configuration. The energy consumed by a sensor node corresponds to that used to transmit its own generated messages and to relay the pass-through traffic of other sensor nodes. Moreover, to better evaluation of the real behavior of WSNs, they considered the wasted energy due to re-transmissions, overhearing, and idle. Authors considered a Network model consists of $V$ nodes. For each sensor node $v$, generated reports to the sink can follow one of the possible $|P(v)|$ paths. They associate a weight $w(p)$ to each path $p \in P(v)$, such that $\sum_{p \in P(v)} w(p) = 1$. Vector $W(v) = (w(p))_{p \in P(v)}$ represents the fraction of utilization of each path $p \in P(v)$ used to send the traffic from node $v$ to the sink node. The average amount of energy consumed by node $u$ per unit of time due to the different transmissions inside the WSN $E(u)$, can therefore be expressed as follows:

$$E(u) = E_{idle}(u) + \sum_{v \in V} \sum_{p \in P(v)} w(p) \times A(v) \times E(u,p)$$

(30)

where $E_{idle}(u)$ is the average amount of energy that is consumed by node $u$ per unit time during idle state, $A(v)$ is the average number of reports sent per unit of time by each sensor node $V$, and $E(u,p)$ is the energy consumed by node $u$ to successful delivery of packet transmitted by node $v$ through path $p$ to sink.

5. CONCLUSION

Energy consumption in WSNs is extremely important due to the limitation of power consumption sources. Better knowledge of the sources of energy consumption in wireless sensor networks is the first step to reduce energy. In this paper, we have given an overview to sources 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. Future work will include, providing a new energy model which capture all energy consumption sources in all communication layers stack. In physical layer, new model should capture energy consumption in hardware components, and impact of channel state, physical overhead and the probability of error. Also in MAC layer, the new model should capture the impact of type of MAC protocols (e.g. Schedule-based MACs and Contention-Based MAC), MAC overhead, overhearing and collisions. In network layer, impact of type routing protocols, energy
wasted in the setup phase of routing protocols and packet loss should be taken into account. With such model the energy consumption can be optimized and lifetime can maximize.

References


