An improved harvested energy management mechanism for wireless sensor networks

Abdelmalek Bengheni[1], Messaoud Hameurlaine[2]
[1]LRAIS Laboratory, Department of Computer Science, Math/CS Faculty, University of Ibn-Khaldoun, Tiaret, Algeria
[2]LEIMA Laboratory, Ahmed Ben Yahia El Wancharissi University, Tissemsilt, Algeria

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ABSTRACT

Wireless sensor networks (WSN) play a vital role in monitoring and communication applications, but their performance is often constrained by limited battery power. Energy harvesting (EH) technologies have emerged as a promising solution to extend network lifetime by supplying supplementary energy from the environment. However, efficiently balancing harvested and consumed energy remains a significant challenge. This paper introduces an improved harvested energy management mechanism (IHE2M) that dynamically adjusts the duty cycle of sensor nodes based on residual energy availability. Unlike traditional approaches that rely on fixed duty cycles, IHE2M allows each node to determine its sleep and active periods adaptively, reducing collisions, idle listening, and unnecessary retransmissions. The mechanism was evaluated through OMNeT++/MiXiM simulations and compared with existing schemes such as EH2M and dynamic source routing (DSR). Results demonstrate that IHE2M achieves higher packet delivery ratios, lower latency, and better throughput while reducing average energy consumption per node. The findings confirm that IHE2M provides a more sustainable and efficient solution for energy-harvesting WSN, improving reliability and extending network lifetime.

Corresponding Author:

Abdelmalek Bengheni
LRAIS Laboratory, Department of Computer Science, Math/CS Faculty, University of Ibn-Khaldoun
BP 78 zaâroura, Tiaret 14000, Algeria
Email: abdelmalek.bengheni@univ-tiaret.dz

1. INTRODUCTION

The activity of the duty cycling node is one of the most basic and often applied power management (PM) strategies during wireless sensor networks (WSN) operation [1], which allows each sensor to alternate between the two states listed: (i) wakeup state: during this state, the node activates its radio in order to sample, calculate, and communicate and (ii) sleep state: a timer is set, and the node shuts down its radio. It immediately transitions to the waking state when the timer's sleep period is up. The majority of the cycle in duty-cycled operation is employed in the stage of low-power sleep. This procedure, which depends on hardware support [2], [3] to achieve sleep states, is necessary since an active node may only communicate for a very small percentage of the active duration, enabling a node's average power consumption to be reduced by many orders of magnitude. The medium access control (MAC) layer manages this type of duty cycle using communication protocols. These MAC protocols can be divided into two categories: asynchronous ones, like RMP-MAC [4], and synchronous ones, like network synchronization (NS)-MAC [5]. However, the network lifetime is still constrained. The integration of an energy harvesting (EH) device [6]-[8] into each sensor node is a relatively recent concept. This allows each node to enter a sleep state to harvest and save energy, thereby reducing its operating time. This is also the basis of the energy harvesting management

(EHM) strategy. The "duty-cycle" approach is really the foundation of the EHM used in most MAC protocols of the EH recommended [9]; these protocols include harvesting energy neutral operation (HENO)-MAC [10]; their goal is to keep the sensor nodes functioning in the energy neutral operation (ENO) state [11]. In other words, energy use is always lower than or equal to the energy that is extracted from the environment, or if its energy consumption is constantly equal to the energy collected, it enters the ENO-Max state. However, most protocols lack predictive mechanisms to adjust duty cycles dynamically, often leading to inefficiencies, collisions, and reduced performance. To address these challenges, this paper introduces the improved harvested energy management mechanism (IHE2M), which adjusts node duty cycles based on residual and prospective energy levels. By optimizing sleep schedules, IHE2M reduces collisions, balances energy usage, and extends the operational lifetime of EH-enabled WSN. This is how the document rest is arranged. Section 2 displays a list of related works. The suggested IHE2M for WSN is explained in the next section 3, and section 4 evaluates and reports the findings. The article is finally concluded in section 5.

2. RELATED WORKS

A recently established approach in WSN that considers the energy impact collecting ratio in compensating for energy consumption is EH, which aims to maintain energy neutrality [12]. Numerous MAC techniques were recently created for EH-WSN in order to overcome this problem. These systems schedule different duties, such as duty cycle, while accounting for the energy collected.

Rasouli *et al.* [13] presented an energy-saving method called the "Adaptive Duty Cycle Algorithm for Energy Efficiency IEEE 802.15.4 Beacon-Enabled WSN (ADCA)". A custom pattern and IEEE 802.15.4 technology are used to automatically set the duty cycle in exact proportion to the traffic data. The proposed ADCA approach is tailored for the beacon-permitted star network of the WSN; it increases the energy efficiency of the system, especially in situations when traffic is very variable and changes over time.

Yoo *et al*. [14] introduced two variable duty cycle planning methods for EH-WSN, with the goal of reducing the sleep delay of sensor node while maintaining the balance of power consumption among them. The initial one, named DSR: duty-cycle scheduling based on residual energy modifies the duty-cycle using the energy that is left behind. In contrast, the following named DSP: duty-cycle scheduling based on the prospective increase in residual energy lowers the duty cycle further vigorously as needed by making use of the potential rise in residual energy over time in EH. To achieve this reduction, the difference among the rates of energy collected and used is computed at the start of each duty cycle.

In Varghese and Jose [15] propose two schemes: the first dynamic duty cycle programming-based emerging demand and supply requirements (EDDSR) MAC protocol uses just the current amount of energy that is left, each sensor node's duty cycle is dynamically adjusted via the first exponential MAC protocol for decision-making. The second scheme "dynamic duty cycle programming" predicts the possible rise in remaining energy during time for each sensor node, which is based on the prospective energy increase (EDDSP). This strategy uses exponential decisions to improve energy efficiency and reduce downtime.

In order to minimize end-to-end network latency, the Park and Ra [16] proposed a MAC technique that modifies the duration of a packet's data transfer based on estimates of the energy needed for the energy collected, data transfer, and the volume of traffic entering the WSN. It does this by building a PM system that tracks the time of EH and uses it to control WSN sleep duration.

According to Sarang *et al*. [17], the ENO-based adaptive duty-cycle mac protocol for solar EH-WSN (ENCOD-MAC) allows the node to function as close to the ENO mode as is practical. Reducing their duty cycle according to battery level and incorporating extra energy collected leads to better WSN performance.

Bengheni [18] propose a multi-threshold energy strategy for EH-WSN (MTE-EHWSN) that aims to reduce the duty cycle of each sensor node to shorten its operating duration. By using a variety of energy thresholds, sensor nodes in MTE-EHWSN can reduce their duty-cycle in accordance with their residual energy, which can rise over time in a more profound and drastic manner.

An energy-harvested management mechanism (EH2M) for WSN is proposed by Bengheni *et al*. [19] in order to decrease the duty cycle based on the current quantity of energy that remains. Every sensor node may automatically change its duty cycle using EH2M through calculating how long it will take to sleep based on the quantity of energy left. Furthermore, the EH2M technique offers a balance between each sensor node EH capacity and consumption in a WSN.

The enhanced energy management scheme in EH-WSN (EEM-EHWSN) is proposed by Bengheni *et al*. [20]. In order to reduce the duty-cycle of each sensor node in the WSN and maintain equilibrium among the EH and energy consumption capabilities, EEM-EHWSN employs receiver-initiated communication to control the sleep/active times by introducing a policy of energy threshold and using the remaining energy.

Bengheni [21] proposed the relay node selection and deep sleep duration (RD-EHWSN) approach for PM in EH-WSN. This approach focuses on controlling the operating cycles of sensor nodes. It uses a power threshold strategy based on the estimated remaining energy of the nodes. This allows the nodes to adjust their activity more efficiently. As a result, overall energy consumption is reduced. The approach also helps balance network energy usage with EH capabilities. In addition, the transmitter uses a short low-power listening message. Relay node selection is applied to distribute the network load evenly.

Wang *et al*. [22] propose a MAC protocol called PSL-MAC in the EH-WSN to stop data accumulation in nodes. PSL-MAC consists of two options: an accumulation, data processing methodology (power control, same-layer transmission, and "layer-down" processing, or PSL) to prevent data accumulation and a probability-based data transmission method for high channel use. The simulation's outcomes show that PSL-MAC effectively solves the problem of data accumulation while boosting WSN throughput and reducing packet loss rate.

A prediction-based adaptive duty cycle MAC protocol (PADC-MAC) was proposed in [23] to optimize WSN performance. Using mathematical computations, it integrates data regarding gathered energy from the present and the future. Furthermore, a nonlinear autoregressive neural network was used as a model to demonstrate prediction accuracy in dynamic harvesting scenarios. Therefore, when enough energy is collected, it enables the receiving node to perform considerably better while conserving its remaining energy.

Hmidi *et al*. [24] proposed a mobility-aware media access control with EH (MEH-MAC), which controls media access in ambient-powered mobile WSN, to solve the issues of mobility and EH. By modifying nodes' active and sleep cycles according to the available power and EH rate, it guarantees that nodes function in the ENO state. MEH-MAC effectively integrates the two ideas so that each is advantageous to the other. While EH employs movement to produce electricity, mobility uses EH to power sensors.

To overcome the limitations of the conventional receiver-initiated MAC protocol, the ground-breaking zero excess node MAC (ZEN-MAC) protocol was introduced in [25]. This protocol deliberately reduces idle listening time by using low-power listening with multistage beacons and clear channel assessment. Additionally, it optimizes intermittent times based on the anticipated power used of the WSN to provide distributed load control. These improvements reduce power use and make the WSN more efficient.

An EH MAC protocol for cognitive WSN (R-MAC), proposed by Obaid *et al*. [26] for cognitive WSN (CWSN), aims to ensure energy autonomy for the network of cognitive sensors by balancing the amounts of energy collected and wasted while keeping throughput and latency within reasonable bounds.

3. PROPOSED IHE2M FOR WSN

The proposed IHE2M mechanism operates by dynamically adapting the duty cycle of each node according to its residual energy. The ratio of active time ($time_i^{active}$) to the total sleep time ($time_i^{sleep}$) and active time is known as the duty cycle of an active node i ($Duty_i^{cycle}$) [27]:

$$Duty_i^{cycle} = \frac{time_i^{active}}{time_i^{active} + time_i^{sleep}} \quad (1)$$

3.1. Energy consumption modeling of the receiver-initiated MAC communication type used

Utilizing the same prior network with n nodes, we study a particular kind of periodic traffic production in which nodes produce data at a predetermined frequency. The energy model's vocabulary is listed in Table 1.

The expected energy consumption $E_i^{cons}(t_{ctrl})$ for control time (t_{ctrl}) by a node i is the sum of the predicted energy consumption in each action j, as shown by the following formula:

$$E_i^{cons}(t_{ctrl}) = \sum_{j\in\{(cs),(es),(tx),(rx)\}} \left(T_j \times C_j\right)(t_{ctrl}) \times V \quad (2)$$

where, cs: carrier sensing, es: environment sensing, tx: transmission, and rx: reception.

Each time it wakes up, the sender waits for the receiver's beacon and measures its surroundings. The receiver checks the channel and then sends a beacon. If the sender wakes up and detects it, it sends its own beacon to request sending a DATA frame.

$$T_{cs} \leq 2T_{acs}R_{data} \quad (3)$$

$$T_{es} = T_{asense}R_{sense} \quad (4)$$

A node's transmission time includes sending a beacon, a data packet, a confirmation beacon, and a W beacon-on-request. After receiving a confirmation beacon, the transmitter switches to listening mode and sends data packets until its queue is empty. If Npq packet data is stored, it can send Qp packets to the same destination when $(1 < Qp \leq Npq)$. During the period when $(W < m \leq n)$, a node may receive $(Qp + W)$ acknowledgement beacons, m beacon-on-request, Qp data packets, and a beacon. When it receives a beacon-on-request, it becomes the target node and sends an acknowledgement beacon once it confirms the packet was received.

$$T_{tx} = R_{data}(L_{beacon} + QpL_{packet} + (Qp + W)L_{abeacon} + WL_{beaconR})T_{(t/r)xb} + (Qp + W + 1)T_{SW} \quad (5)$$

$$T_{rx} = R_{data}(L_{beacon} + QpL_{packet} + (Qp + W)L_{abeacon} + mL_{beaconR})T_{(t/r)xb} + (Qp + W)T_{SW} \quad (6)$$

with: $W \in \{0,1\}$.

Table 1. Terms used energy model

Term	Meaning
C_j (mA)	Current consumption of action j
V	Voltage
T_j	Time spent by action j
R_{data}	Rate a data packet to TX/RX
R_{sense}	Rate of environmental sensing
L_{beacon}	Beacon packet length
$L_{beaconR}$	Beacon-on-request packet length
L_{packet}	Data packet length
$L_{abeacon}$	Acknowledgement beacon packet length
T_{acs}	Average carrier sense time
T_{asense}	Average time for data sampling
$T_{(t/r)xb}$	Time to send/receive a byte
T_{cs}	Time of carrier sense
T_{es}	Time of environment sense
T_{tx}	Time of transmission
T_{rx}	Time of reception
T_{sw}	Radio switching time

3.2. Formulation of optimization problems

We study a periodic form of EH where nodes collect environmental energy (e.g., solar) that rises and falls in a regular, predictable cycle, shaping when they can sense or communicate. We consider a WSN with n sensor nodes. Every node has a variety of units, such as a processing unit, an analog to digital converter (ADC), surroundings detecting unit, and several kinds of memory (flash memories, data and programmed), a communication unit (RF transceiver), an EH system, and a power unit with the maximum capacity (E_i^{max}). Every node also uses an energy threshold (E^{thre}) to conserve equilibrium between EH capacity and energy consumption, defined by the administrator. Two optimization problems are defined: (i) ($OP1$-pb) minimizing node duty cycle while ensuring energy neutrality, and (ii) ($OP2$-pb) maximizing remaining energy utilization over time. Sleep duration is determined using predictive equations that consider harvested energy probability, such that: $E_i^{rem}(t_{ctrl})$: represents the remaining energy of node *i* at the control time (t_{ctrl}), $time_i^{sleep}$: Represents node *i*'s sleep time at t_{ctrl} of $(E_i^{rem}(t_{ctrl}))$ can be determined by one of the following (7a) or (7b) based on E^{thre} and E_i^{max}.

$$time_i^{sleep}\left(E_i^{rem}(t_{ctrl})\right) = \frac{E_i^{max} - E_i^{rem}(t_{ctrl})}{E_i^{max} - E^{thre}} \times Time_{Ste_i} \quad (7a)$$

when, $Time_{Ste_i}$ is calculated:

$$time_i^{sleep}\left(E_i^{rem}(t_{ctrl})\right) = e^{\log_2\left(\frac{E_i^{max} - E_i^{rem}(t_{ctrl})}{E_i^{max} - E^{thre}} \times Time_{Ste_i}\right)} \quad (7b)$$

when, $Time_{Ste_i}$ is not calculated, with:

$$Time_{Ste_i} = \min(Time_{Ste_i}, 1) \quad (8)$$

where, $Time_{Ste_i}$: the amount of time that node i sleeps until its remaining energy hits the energy threshold E^{thre}.

– $OP1 - pb$

$$minimize\ Duty_i^{cycle} \forall i \in \{1, \dots, n\} \tag{9}$$

Subject to:

$$time_i^{active} \leq time_i^{active} + time_i^{sleep} \tag{9a}$$

$$time_i^{active} + time_i^{sleep} \neq 0 \tag{9b}$$

$$E^{thre} \leq E_i^{rem}(t_{ctrl}) \leq E_i^{max} \tag{9c}$$

$$0 < E^{thre} < E_i^{max} \tag{9d}$$

$$0 < t_{ctrl} \tag{9e}$$

$$time_i^{active},\ time_i^{sleep} \geq 0 \tag{9f}$$

– $OP2 - pb$

$$maximize\ E_i^{rem}(t_{ctrl})\ \forall i \in \{1, \dots, n\} \tag{10}$$

where, $E_i^{rem}(t'_{ctrl})$: is the remaining energy at preceding t'_{ctrl}. $E_i^{cons}(t_{ctrl} - t'_{ctrl})$, $E_i^{harv}(t_{ctrl} - t'_{ctrl})$: explain the consumed quantity calculated by using (1) and the harvesting quantity within identical time interval $(t_{ctrl} - t'_{ctrl})$ correspondingly. Subject to:

$$E_i^{rem}(t_{ctrl}) = \left(E_i^{rem}(t'_{ctrl}) - E_i^{cons}(t_{ctrl} - t'_{ctrl})\right) + E_i^{harv}(t_{ctrl} - t'_{ctrl}) \tag{10a}$$

$$E_i^{rem}(t_{ctrl}) \geq E^{thre} \tag{10b}$$

$$E_i^{rem}(t'_{ctrl}) \geq E_i^{cons}(t_{ctrl} - t'_{ctrl}) + E_i^{harv}(t_{ctrl} - t'_{ctrl}) \tag{10c}$$

$$E^{thre} \leq E_i^{rem}(t_{ctrl}) \leq E_i^{max} \tag{10d}$$

$$0 < E^{thre} < E_i^{max} \tag{10e}$$

$$0 < t'_{ctrl} < t_{ctrl} \tag{10f}$$

$$E_i^{rem}(t'_{ctrl}), E_i^{cons}(t_{ctrl} - t'_{ctrl}), E_i^{harv}(t_{ctrl} - t'_{ctrl}) \geq 0 \tag{10g}$$

3.3. Improved harvested energy management mechanism

The node activity duty-cycling using IHE2M is fixed at the beginning, with the administrator fully determining the active and sleep times. It then becomes dynamic based on the pace where energy may be gathered after $E_i^{rem}(t_{ctrl}) < E^{thre}$ as shown in Figure 1.

At each cycle, nodes assess their current residual energy. Nodes with higher energy remain active longer, while those with lower energy extend their sleep time. This adaptive scheduling reduces the likelihood of neighboring nodes waking simultaneously, thereby minimizing collisions. Therefore, in order to store an ensured energy level and to store as much energy as possible, a node with less energy decides to sleep for a longer period of time. The following process determines $time_i^{sleep}$ using IHE2M:

(i) Before entering the sleep state, every node i in the waking state examines how much energy it still has.
(ii) The node i uses (8) to determine the $Time_{Ste_i}$ in the sleep state if $(E_i^{rem}(t_{ctrl}) < E^{thre})$ until its residual energy reaches the E^{thre}.
(iii) In subsequent wake-ups, node i uses either (7a) or (7b) to determine its $time_i^{sleep}$ when $E_i^{rem}(t_{ctrl}) \geq E^{thre}$; otherwise, it executes steps (i), (ii), and (iii) respectively.

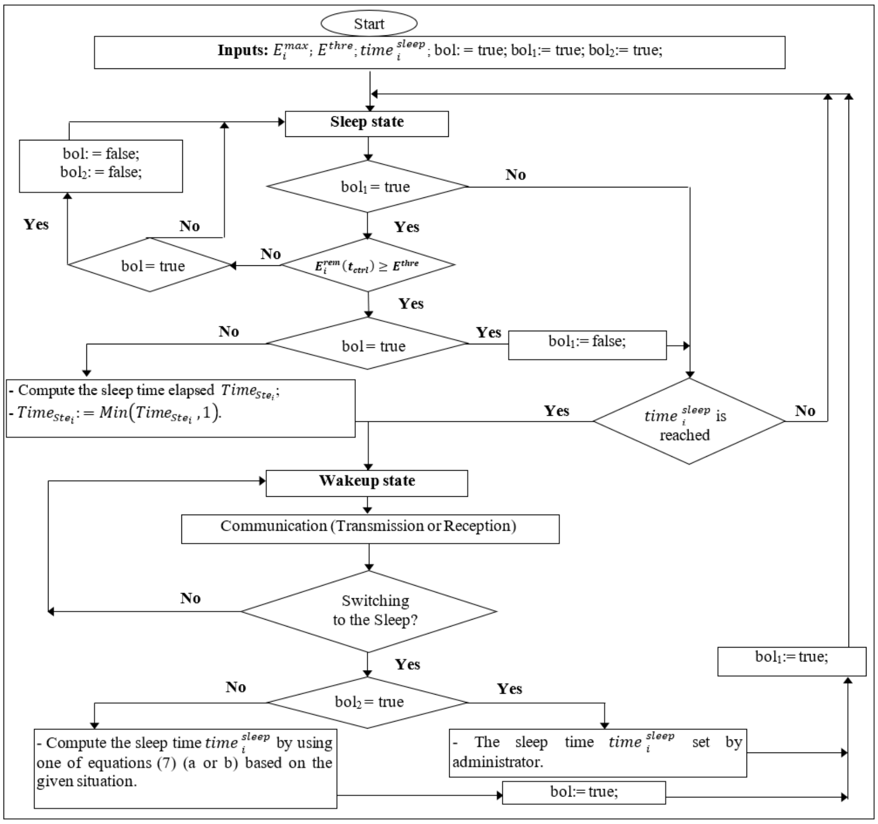

Figure 1. Fundamental operations of the IHE2M system for WSN

4. RESULTS AND DISCUSSION

4.1. Performance measures used

Performance is evaluated through OMNeT++/MiXiM [28] simulations under varying node densities and harvesting rates. Key metrics include mean packet latency (MPL), packet delivery ratio (PDR), throughput ($THRG$), average energy consumption per node ($Avge(CSE)$), and network lifetime ($Netlife$).
$Mean\ Packet\ Latency$: this is the average amount of time the packet takes to reach the target node across all packets. It is calculated as:

$$MPL = \frac{\sum_{k=1}^{Nbr_{tx}^{Pkt}} Latency_k}{Nbr_{tx}^{Pkt}} \quad (11)$$

with, Nbr_{tx}^{Pkt}: is the sum of packets transmitted number, $latency_k$: the latency of packet k, and $packet\ delivery\ ratio$: this is the sum of the packets received by the receiver (Nbr_{rx}^{Pkt}) divided by the overall packets sent number (Nbr_{tx}^{Pkt}) by the senders. It is calculated as:

$$PDR = \frac{Nbr_{rx}^{Pkt}}{Nbr_{tx}^{Pkt}} \quad (12)$$

$Average\ energy\ consumption\ per\ node$: the average energy expenditure (CSE) by all nodes in the network divided by the number of nodes (Nbr) displayed by $Avge(CSE)$ in the (13), which should be minimized.

$$Avge(CSE) = \frac{\sum_{i=1}^{Nbr} CSE_i}{Nbr} \quad (13$$

where:

$$CSE_i = \text{consumed energy per node } i/\text{simulation time} \quad (14)$$

Network throughput: the quantity of data packets collected by the recipient during the simulated period ($simulation\ time$) is referred to as the average network throughput ($Net_{Througput}$), as shown:

$$Net_{Througput} = \frac{N_{tr}^{pkt} \times packetsize}{simulation\ time} \quad (15)$$

with, N_{tr}^{pkt}: transmitted packets number. $Network\ lifetime$: this occurs when the initial sensor's power is depleted and it loses the ability to transmit data while it is being collected.

$$Netlife = \left(\frac{E_{Net-init}}{E_{Net-cons}}\right) \times simulation\ time \quad (16)$$

where, $E_{Net-init}$: the network's initial energy, and $E_{Net-cons}$: the energy amount that the WSN consumed.

4.2. Performance evaluation

The IHE2M mechanism was compared against the EH2M and DSR schemes, which employ a dynamic duty cycle similar to IHE2M, and were combined with receiver-initiated MAC (RI) communications. Table 2 displays the different additional parameters of simulation that were employed.

Our results come from a simulation involving 16 sensor nodes distributed over a 400×400 m² area, up to 100 sensor nodes distributed over a 1100×1100 m² area. The simulation lasted 1000 seconds and involved a distance of 100 meters between two neighbors in the grid. The EH time corresponds to 0.1 (Harvesting Param) seconds for all sensor nodes, and the nodes of each source sensor can transmit their periodic traffic (traffic param) to the sink every 1.5 seconds via multi-hop transmissions. The amount of energy gathered is chosen at random from a predetermined range of [0 mW...50 mW]. Every sensor node has a 30 J energy threshold, a maximum energy value of 100 J, and a starting energy of 50 J.

Table 2. Parameters of simulation

Parameter	Value
Number of nodes	16, 25, 49, 64, 100
Topology	Grid
Simulation time	1000 s
Size of playground (X×X m²), X =	400, 600, 800, 950, 1100
Initial remaining energy E_i^{rem}	50 J
Energy threshold E^{thre}	30 J
Traffic type	Periodic
Traffic parameter	1.5 s
Number of packets sent	500
Destination node	15, 24, 48, 63, 99
Queue size	10 packets
Battery capacity	100 J
Harvesting type	Periodic
Harvesting parameter	0.1 s
Harvesting rate randomly	[0 mW...50 mW]

The results that were obtained for the PDR measure is displayed in Figure 2. We find that when the nodes number increases, the PDR falls. The findings validate that, as the nodes number rises with a varying EH rate, RI-IHE2M performs better than RI-EH2M and RI-DSR. This outcome is the consequence of each sensor node's ability to precisely and efficiently dynamically alter its duty cycle in response to the energy that remains. Since their neighbors are unlikely to be comparable, the sleep durations are purposefully set to drastically lower collisions and retransmissions when compared to RI-EH2M and RI-DSR.

The simulation results are displayed in Figure 3 for an MPL metric, 500 sent packets, a traffic parameter of 1.5 seconds, and a number of nodes ranging from 16 to 100. According to the findings, RI-IHE2M performs noticeably better than RI-EH2M and RI-DSR. It's important to note that RI-IHE2M has a lower MPL than RI-EH2M and RI-DSR due to its more precise and efficient duty cycle minimization. This is dependent on how much energy remains at each node in the WSN, which might grow over time and shorten its active period. Its sleep duration, which can be either short or lengthy, is calculated using (7b) or (7a). In contrast to RI-EH2M and RI-DSR, RI-IHE2M lowers the likelihood that packets will be buffered, which lowers its MPL. This is because nodes balance their energy use and harvesting, which lessens the possibility that nodes in the same vicinity may wake up simultaneously.

The simulation results for the $THRG$ measure, expressed in bits per second (bps), are displayed in Figure 4. The findings demonstrate that RI-IEH2M can produce a greater $THRG$ than both RI-EH2M and RI-DSR due to the dynamically reduced sensor nodes' activity period, which is highly efficient and accurate, depending on the different amounts of harvested energy. This significantly reduces collisions and the number of retransmissions over RI-EH2M and RI-DSR. The more collisions occur, the longer the time is required for effective communication, which causes packet loss. Also, RI-EH2M and RI-DSR provide lower $THRG$ due to the use of a less efficient dynamic activity period for sensor nodes, and they do not utilize the available future energy to adjust the sensor nodes' duty cycles effectively.

Figure 5 shows that at different EH rates, RI-IHE2M exhibits a better energy saving metric than RI-EH2M and RI-DSR. This is due to RI-IHE2M's use of two types of idle times: a short one calculated using (7b) and a long one calculated using (7a), which are not used by RI-EH2M and RI-DSR. Every sensor node has the ability to dynamically modify its duty cycle with high efficiency and precision, which is more profound than RI-EH2M and RI-DSR, based on the remaining energy that may rise in time. RI-IHE2M intentionally selects sleep times that are unlikely to be similar for the neighborhood of sensor nodes in a WSN, thus reducing collisions and retransmissions, which are believed to be the main causes of high energy consumption and frequent failures during data communication within the WSN.

From the results achieved for the $Netlife$ metric presented in the Figure 6, we observe that the latter rises with the rise in the number of nodes using these three schemes: RI-IHE2M, RI-EH2M, and RI-DSR, for different EH rates. RI-IHE2M exhibits better performance in terms of prolonging the $Netlife$ over RI-EH2M and RI-DSR. This is because each sensor node is able to dynamically modify its duty cycle with high efficiency and precision. This is further profound than RI-EH2M and RI-DSR, as it determines the time of its next sleep period, its length being determined by (7b) and (7a). This helps provide load balancing among nodes in the WSN, because it prolongs the $Netlife$ by ensuring that relay nodes do not depart or run out of energy entirely after cooperating. Due to their shorter sleep duration, RI-IHE2M also promotes node activity with increased energy levels.

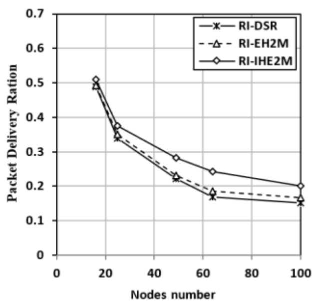

Figure 2. Packet delivery ratio

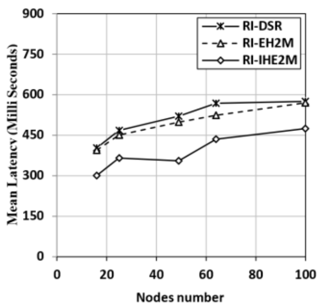

Figure 3. Mean latency

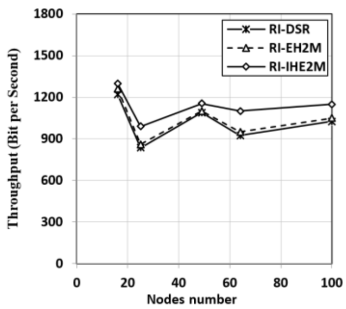

Figure 4. Throughput

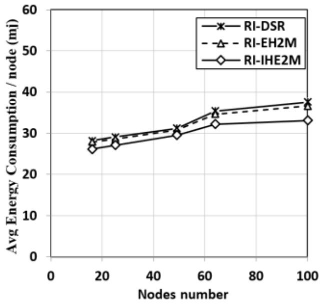

Figure 5. Average energy consumption per node

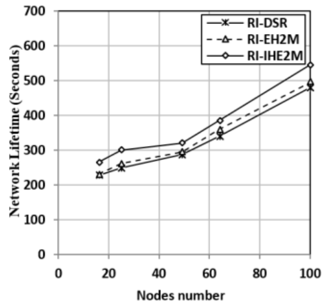

Figure 6. Network lifetime

In Table 3, three dynamic duty cycle schemes were evaluated by averaging all of the outcomes of a chosen scheme at a specific traffic parameter. It is obvious that dynamic duty cycle IHE2M outperforms others (EH2M and DSR) in terms of packet delivery ratio, mean latency, throughput, energy saving, and WSN lifetime.

As a result, by efficiently minimizing the duty cycle, the performance of the WSN can be improved in terms of energy saving, latency, packet delivery ratio, throughput, and network lifetime in energy-harvesting environments. It is also important to reduce energy waste caused by collisions and high node activity [14], [20]. Compared to RI-EH2M and RI-DSR, RI-IHE2M shows clear improvements in latency, packet delivery ratio, throughput, average energy consumption per node, and overall WSN lifetime. By providing additional harvested energy, IHE2M allows nodes to wake up more often and transmit data faster, which improves latency and throughput. However, higher activity increases power consumption, and when harvested energy is insufficient, nodes must return to longer sleep periods, which may increase latency [14]. Therefore, IHE2M achieves better performance while requiring a careful balance between energy availability and network responsiveness.

IHE2M may face difficulties when harvested energy changes rapidly. Since it relies on future energy prediction, sudden energy drops can cause nodes to schedule more activity than they can support, leading to power instability, synchronization loss, or long inactive periods [29]. In multi-hop networks, unequal energy distribution can create bottlenecks when low-energy nodes slow down or interrupt data forwarding, while simultaneous energy increases at multiple nodes may result in channel congestion and reduced throughput, especially under variable harvesting conditions [30]. Extended low-energy periods can also increase recovery time due to costly resynchronization. As IHE2M is designed for relatively stable energy conditions, it may perform poorly under strict timing constraints or highly variable traffic patterns [31]. Overall, IHE2M performs well in stable environments but remains sensitive to rapid energy variations, uneven harvesting, synchronized energy surges, and tight timing requirements. Therefore, evaluating its behavior under small energy and traffic fluctuations is essential to improve its robustness.

Table 3. Performance evaluation of DSR, EH2M and IHE2M with different metrics

Performance metrics	Results evaluation
PDR (%)	– From Figure 2, the PDR results show that IHE2M performs better than EH2M and DSR. When the WSN size increases from 49 to 100 nodes, the PDR decreases by 41.48% for IHE2M, 38.66% for EH2M, and 46.36% for DSR. With 100 nodes, IHE2M achieves a performance improvement of about 16.74% compared to EH2M and 24.54% compared to DSR. – EH2M performs well better than DSR. When the number of nodes is 100, EH2M achieves a significant performance gain of roughly 16.74% in PDR over DSR.
MPL (milli seconds)	– From Figure 3, The MPL results show that IHE2M performs better than DSR and EH2M. With 16 nodes, IHE2M improves MPL by about 25.56% compared to DSR and 23.86% compared to EH2M. When the network size increases to 100 nodes, the improvement remains significant at around 17.39% and 16.67%, respectively. – EH2M performs well better than DSR. When the number of nodes is 100, EH2M achieves a significant performance gain of roughly 0.87% in MPL over DSR.
$THRG$ (bit/second)	– Frome Figure 4, the results show that IHE2M achieves higher *THRG* than EH2M and DSR. At 16 nodes, the $THRG$ increases by about 3.00% compared to EH2M and 6.15% compared to DSR. At 100 nodes, the improvement rises to around 8.70% and 10.87%, respectively. – EH2M performs well better than DSR. When the number of nodes is 100, EH2M achieves a significant performance gain of roughly 2.38% in $THRG$ over DSR.
$Avge$ (CSE) (milli joule) ($Energy\ saving$)	– From Figure 5, the Energy saving (ES) results show that IHE2M saves more energy than DSR and EH2M. With 16 nodes, ESs increase by about 7.55% compared to DSR and 6.26% compared to EH2M. When the network size reaches 100 nodes, the improvement rises to around 13.47% and 10.73%, respectively. – EH2M performs well better than DSR. When the number of nodes is 100, EH2M achieves a significant performance gain of roughly 2.48% in MPL over DSR.
$Netlif$ (seconds)	– From Figure 6, the $Netlife$ results show that IHE2M extends network lifetime compared to DSR and EH2M. With 16 nodes, $Netlife$ improves by about 13.96% over DSR and 12.83% over EH2M. When the network grows to 100 nodes, the improvement remains at around 11.93% and 9.17%, respectively. – EH2M performs well better than DSR. When the number of nodes is 100, EH2M achieves a significant performance gain of roughly 3.03% in *Netlife* over DSR.

5. CONCLUSION

This paper presented IHE2M, an IHE2M for WSN. By dynamically adjusting duty cycles based on residual energy, IHE2M significantly reduces collisions, improves packet delivery ratio, decreases latency, and enhances throughput compared with EH2M and DSR. Simulation results confirm that IHE2M also reduces average energy consumption per node and extends overall network lifetime. These improvements demonstrate the effectiveness of adaptive duty-cycling for EH-WSN. Future work will explore integrating predictive models of environmental energy availability (e.g., solar irradiance datasets) and applying IHE2M to large-scale deployments with heterogeneous sensor nodes, considering varying traffic conditions and operating cycles, as well as a variable energy threshold that all nodes will utilize, which can be determined based on node mobility and remaining energy

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Abdelmalek Bengheni	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	
Messaoud Hameurlaine		✓	✓	✓							✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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BIOGRAPHIES OF AUTHORS

Abdelmalek Bengheni received an Engineering degree from the Oran University (Algeria) in 1998 and the Magister diploma from the Mascara University (Algeria) in 2008. In 2019, he obtained his Ph.D. in Computer Science from the University Abou Bekr Belkaid. He is a member and researcher at the LRAIS, Laboratory of Research in Artificial Intelligence and Systems of Tiaret. He is actually Assistant Professor in the Department of Computer Science, at IBN Khaldoun Tiaret University. His research interests include wireless sensor networks, MAC protocol design and energy harvesting technologies. He can be contacted at email: abdelmalek.bengheni@univ-tiaret.dz.

Messaoud Hameurlaine received the Ph.D. degree in Computer Science in 2017 from Amar Telidji University of Laghouat, Algeria. He is a senior researcher and Head of the Smart Technologies Research Team at the LEIMA Laboratory, University of Tissemsilt, Algeria. He is currently an Assistant Professor at the Faculty of Sciences and Technologies, Ahmed Ben Yahia El Wancharissi University of Tissemsilt, Algeria. His research interests include machine learning, deep learning, smart technologies, healthcare systems, and medical image analysis. He has published extensively in reputable international journals and conferences in his research fields and serves as a reviewer for several indexed scientific journals. He can be contacted at email: hameurelaine.messaoud@univ-tissemsilt.dz.