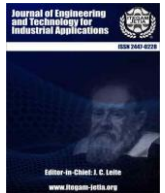




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RESEARCH ARTICLE

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E2A2S-WSN: ENERGY-EFFICIENT ADAPTIVE SLEEP SCHEDULING FOR LOAD-BALANCED EH-WSNS

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ABSTRACT

This paper proposes E2A2S-WSN, an Energy-Efficient Adaptive Sleep Scheduling for Load-Balanced energy harvesting wireless sensor networks based on asynchronous duty cycling and relay node selection. The scheme dynamically adapts node duty cycles using a novel level-based strategy that considers residual and harvested energy, ensuring balanced energy consumption across the network. E2A2S-WSN also employs low-power listening with short preambles and an optimized relay selection mechanism to achieve load balancing. E2A2S-WSN scheme was compared with RDEHWSN under various multi-hop traffic and energy harvesting scenarios. Simulation results show that E2A2S-WSN significantly improves network performance by reducing energy consumption and latency, increasing packet delivery ratio and throughput.



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I. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of a large number of low-cost, resource-constrained sensor nodes that cooperatively monitor physical environments and forward sensed data to a sink node [1]. Despite their wide applicability, WSNs are primarily constrained by limited battery capacity, making energy efficiency and network lifetime critical design issues [2]. Since battery replacement is often impractical, numerous energy-saving techniques such as duty cycling, clustering, and load balancing have been proposed at the MAC layer [3-5]. Recently, energy harvesting (EH) has emerged as a promising solution to enable long-term autonomous operation by allowing sensor nodes to exploit ambient energy sources [6]. Accordingly, several EH-aware MAC protocols have been introduced to adapt node activity based on harvested energy. However, most existing approaches rely on reactive duty-cycling mechanisms that do not anticipate future energy availability, leading to uncertain wake-up scheduling, increased latency, and unreliable routing performance in multi-hop scenarios. In addition, the lack of publicly available implementation codes limits reproducibility and fair comparison among EH-WSN protocols [7]. In this paper, we propose E2A2S-WSN Energy-Efficient Adaptive Sleep Scheduling for Load-Balanced Energy Harvesting Wireless Sensor Networks (EH-WSNs), which extends and improves the RDEHWSN scheme [8]. The proposed scheme integrates an energy harvesting module into each sensor node and adopts a transmitter-initiated communication mechanism based on low-power listening with short preambles. This design builds upon the advantages of existing transmitter-initiated MAC protocols [9], [10]. E2A2S-WSN introduces an energy threshold-based approach that exploits residual and harvested energy to dynamically adapt node duty cycles. A novel sleep period estimation method, based on Newton interpolation and residual energy prediction, is employed to more aggressively adjust node sleep durations according to anticipated future energy availability. In addition, a new relay node selection strategy is incorporated to ensure load balancing during data routing. The main objectives of E2A2S-WSN are to reduce energy consumption and average latency while improving packet delivery ratio and throughput. The remainder of this paper is organized as follows: Section 2 reviews related work; Section 3 describes the proposed E2A2S-WSN scheme; Section 4 presents the simulation setup and parameters; Section 5 evaluates and compares the proposed scheme with RDEHWSN; and Section 6 concludes the paper and outlines future research directions.

II. RELATED WORK

Energy harvesting is a promising approach in WSNs that enables sensor nodes to convert ambient energy into usable electrical power, thereby extending network lifetime. To support Energy Neutral Operation (ENO), where energy consumption does not exceed harvested energy, several duty-cycle based MAC protocols have been proposed [11-13]. These protocols are primarily asynchronous and rely on receiver-initiated beaconing mechanisms to adapt node activity to available energy.

II.1 PROBABILISTIC POLLING EH-WSN MAC PROTOCOL

Probabilistic polling is a MAC approach for energy-harvesting WSNs designed to reduce data packet collisions. In this scheme, each receiver periodically broadcasts a polling packet with a contention probability (*Probcon*) that informs sender nodes of their likelihood to transmit. Upon receiving a poll, a sender generates a random number; it transmits if the number is less than *Probcon*, otherwise it may enter charging mode or wait for the next poll. The contention probability is dynamically adjusted: it increases if no data is received and decreases after collisions. Several protocols utilize this principle:

PPMAC [14] targets single-hop WSNs and applies an Additive Increase Multiplicative Decrease (AIMD) strategy to adapt contention probability, improving throughput, fairness, and supporting high node densities.

EHMAC [15] extends PPMAC to multi-hop networks, dynamically adjusting polling packets to reduce interference while considering spatial and temporal variations in harvested energy.

MTTP [16] introduces a tier-based multi-hop scheme fully powered by energy harvesting and validated experimentally on commercial devices, demonstrating feasibility in practical deployments.

These protocols improve throughput, fairness, and scalability by balancing energy consumption and reducing collisions. However, they suffer from high latency, as packets may wait long periods before transmission when contention probability is low, leading to wasted energy and bandwidth in multi-hop scenarios.

II.2 NON-PROBABILISTIC POLLING EH-WSN MAC PROTOCOL

Several MAC protocols for energy-harvesting WSNs have been proposed using alternatives to probabilistic polling, such as CSMA/CA or duty-cycle-based strategies. QAEEMAC [17] employs a data priority scheme and adapts wake-up periods according to node energy to reduce consumption. ERIMAC [18] leverages receiver-initiated communication and packet sequencing with queuing based on neighbouring energy to optimize efficiency and latency. ODMAC [19] supports nodes with diverse energy levels by duty-cycling to match consumption to harvested energy. ELMAC [20] divides the super frame into sensing, contention, and transmission intervals, prioritizing low-energy secondary users while protecting primary users. LEBMAC [21] balances load and energy by controlling duty cycles and routing packets through available awake nodes. DeepSleep [22] enhances IEEE 802.11 PSM for EH devices via a deep-sleep algorithm that reduces contention and improves energy efficiency. DSR and DSP [23] adjust duty cycles based on remaining and anticipated energy to maintain balance and reduce sleep latency. EEM-EHWSN [24] uses an energy threshold strategy to optimize active/sleep intervals, throughput, latency, and packet delivery, though it may be challenged by low node density or long harvesting intervals. Finally, the RDEHWSN scheme [8] uses preamble sampling and low-power listening to adapt sleep periods based on residual energy. It also selects relay nodes during routing to balance the load among sensors, improving throughput, latency, and packet delivery. Although such protocols enhance energy efficiency and network stability, challenges remain in multi-hop networks, variable energy availability, and reliable connectivity.

III. MATERIALS AND METHODS

III.1 E2R-EHWSN SCHEME ARCHITECTURE

This section describes the E2A2S-WSN architecture, which combines relay node selection with sleep scheduling to optimize energy control in energy-harvesting WSNs. The scheme leverages an energy level-based strategy, defined by three administrator-set levels, to balance energy harvesting while maintaining enough active nodes to ensure reliable network communication.

1- E_{CTH} (Completion Threshold): The energy sufficiency level ensures that relay nodes have enough power to perform essential tasks, including data transmission and reception, in the active state.

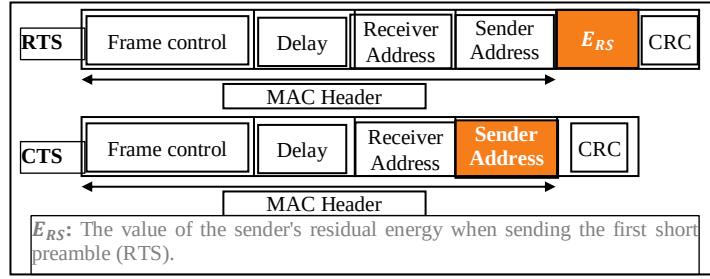
2- Sleep duration levels: Two supplementary energy levels are used to calculate the upcoming sleep interval, optimizing each node's duty cycle according to predicted residual and harvested energy:

2.1- E_{ML} (Minimum required Level): ensures that a node maintains a safe energy level during sleep.

2.2- E_{AL} (Allowed Level): maintains balance between energy consumption and harvesting capacity across the network.

III.1.1 Relay Node Choice Procedure

E2A2S-WSN belongs to preamble sampling MAC schemes with a sender-initiated approach. It leverages harvested energy to operate a dynamic duty-cycle, reducing energy waste. Unlike BMAC [9], nodes are not cyclically synchronized, which can lead to repeated participation in data routing and energy imbalance. To address this, minor modifications were made to the RTS and CTS messages without violating the IEEE 802.11 standard. Fig. 1 illustrates the adjusted message structures.



1. Its residual energy is greater than or equal to that of the sender:

$$E_{RR} \geq E_{RS} \quad (3)$$

2. Its residual energy is lower than that of the sender, but its effective energy exceeds the minimum threshold:

$$E_{RR} < E_{RS} \text{ and } E_{EFF} \geq E_{TH} \quad (4)$$

3. If none of these conditions is met, the node remains silent and does not participate in the forwarding process.

This relay node choice mechanism enables energy-aware and adaptive forwarding, promotes load balancing among nodes, and reduces unnecessary energy depletion, thereby extending the network lifetime without violating IEEE 802.11 MAC principles.

III.1.2 The Main Communication Mechanism of E2A2S-WSN

E2A2S-WSN adopts a communication procedure similar to RDEHWSN and relies on the CSMA/CA protocol to mitigate packet collisions among sensor nodes. Nodes with buffered data listen to the channel after each short RTS preamble and initiate data transmission only upon receiving a corresponding CTS. To enhance energy efficiency, E2A2S-WSN enables nodes to harvest energy and operate under an adaptive duty-cycle, alternating between active and sleep states. Two duty-cycle modes are supported: a fixed mode configured by the system manager and a variable mode dynamically adjusted according to the harvested and residual energy levels.

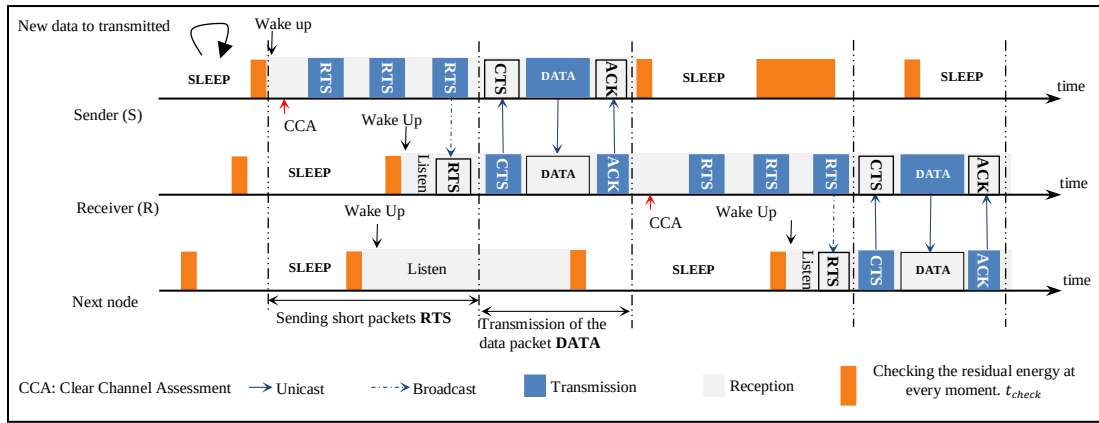


Figure 3: Illustrative diagram of the proposed E2A2S-WSN scheme operation.

Source: Author, (2026).

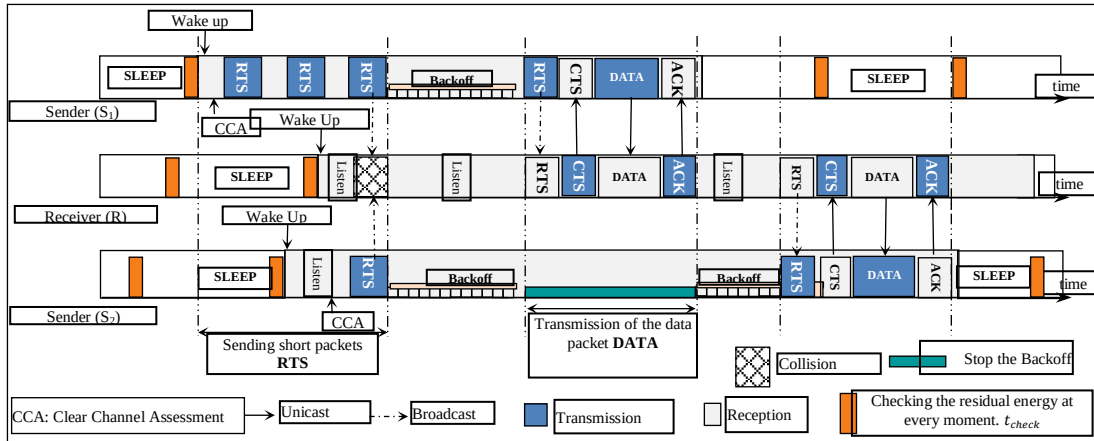


Figure 4: The collision avoidance mechanism incorporated into the proposed E2A2S-WSN scheme.

Source: Author, (2026).

Figures 3 and 4 illustrate the core communication mechanism of the E2A2S-WSN scheme between a sender and a receiving node. In this scheme, each sensor node periodically wakes up according to its own schedule to transmit data when available and switches back to sleep mode in the absence of traffic. Once the radio is activated, the sender node S initiates a preamble phase by broadcasting a sequence of short RTS packets to announce its readiness to transmit, after verifying channel availability using Clear Channel Assessment (CCA). An awake receiving node R, selected as a relay based on predefined criteria, responds with a unicast CTS packet once its backoff timer expires. Upon receiving the CTS, the sender immediately stops sending further RTS packets and transmits the data packet, provided that the channel remains free. The receiver then acknowledges successful reception by sending an ACK packet. After receiving the ACK, the sender switches directly to sleep mode. The receiver subsequently forwards the data to the next hop by repeating the same communication procedure.

III.1.3 Analytical Modeling of the E2A2S-WSN Scheme

This section introduces analytical models for energy consumption and latency in the E2A2S-WSN scheme. The network is assumed to consist of n mobile nodes operating under a static cyclic traffic pattern, where each node generates data at a fixed periodic interval. Table 1 presents the main parameters and their descriptions used in the energy and latency model.

Table 1: Symbols used in the E2A2S-WSN model.

Symbol	Description
$E_i^{Wakeup}(t)$	Total wake-up energy consumed by node i during interval t
$E_i^{cs}(t)$	Energy consumed in carrier sensing during interval t
$E_i^{es}(t)$	Energy consumed in environmental sensing during interval t
$E_i^{tx}(t)$	Energy consumed during transmission during interval t
$E_i^{rx}(t)$	Energy consumed during reception during interval t
P_{cs}	Power consumption in carrier sensing mode
P_{es}	Power consumption in environmental sensing mode
P_{tx}	Transmission power
P_{rx}	Reception power
$T_{cs}(t)$	Carrier sensing duration over interval t
$T_{es}(t)$	Environmental sensing duration over interval t
$T_{tx}(t)$	Transmission duration over interval t
$T_{rx}(t)$	Reception duration over interval t
$T_q(t)$	Packet queuing duration over interval t
$T_p(t)$	Packet processing duration over interval t
T_{acs}	Average duration of one carrier sensing operation
T_{asense}	Average duration of one environmental sensing operation
R_{data}	Data packet generation rate
R_{es}	Environmental sensing rate
L_{packet}	Data packet size
L_{CTS}	CTS packet size
L_{ack}	ACK packet size
T_{bit}	Time required to transmit one bit
T_{SW}	Switching time between TX and RX modes

Source: Author, (2026).

The expected energy consumption of node i in the E2A2S-WSN scheme during the wake-up interval t is determined by the energy spent on carrier sensing (cs), environmental sensing (es), packet transmission (tx), and packet reception (rx), as expressed in Equation (5).

$$E_i^{Wakeup}(t) = E_i^{cs}(t) + E_i^{es}(t) + E_i^{tx}(t) + E_i^{rx}(t) = P_{cs}T_{cs}(t) + P_{es}T_{es}(t) + P_{tx}T_{tx}(t) + P_{rx}T_{rx}(t) \quad (5)$$

Before transmitting the preamble, the node performs carrier sensing at each wake-up period and also activates its environmental sensors to monitor physical parameters. The total durations of carrier sensing and environmental sensing over an interval t are given by equations (6) and (7) respectively, which scale linearly with the observation interval.

$$T_{cs}(t) = T_{acs}R_{data}t \quad (6)$$

$$T_{es}(t) = T_{asense}R_{es}t \quad (7)$$

During a time interval t , the total transmission time of a data packet by node i is the sum of the durations required for sending the RTS, the Data packet, and the corresponding acknowledgments: CTS (in response to the RTS) and ACK (in response to the Data). Before transmitting the Data packet, the node first sends an RTS for a duration T_{SP} and immediately switches its radio to listening mode to receive the CTS. This procedure may be repeated K times if multiple RTS attempts are needed. Upon receiving the Data packet, the receiver immediately switches its radio to transmit an ACK back to the sender, completing the transmission cycle.

$$T_{tx}(t) = t.R_{data}(L_{packet} + L_{CTS} + L_{ack})T_{bit} + KT_{SP} + (K + 2)T_{SW} \quad (8)$$

During a time interval t , a node may receive multiple RTS preambles, data packets, and corresponding acknowledgments (CTS and ACK). For each received RTS preamble, the target receiver immediately replies with CTS, allowing the transmitter to send its data packet. Upon receiving the data, the receiver sends an ACK, completing the transmission cycle. The total number of these exchanges and the associated durations accumulate over the interval t , contributing to the node's overall communication time and energy consumption.

$$T_{rx}(t) = t.R_{data}(L_{packet} + L_{CTS} + L_{ack})T_{bit} + \sum T_{SP} + 2T_{SW} \quad (9)$$

Before transmitting a buffered data packet, the sending node first transmits one or more RTS preambles. Upon receiving the RTS and the subsequent data packet, the receiver responds with the corresponding CTS and ACK acknowledgments. Based on equations (6), (8), and (9), the expected transmission latency can be expressed as:

$$\begin{aligned} L_{atcy}(t) &= T_q(t) + T_p(t) + T_{cs}(t) + T_{tx}(t) + T_{rx}(t) \\ &= T_q(t) + T_p(t) + T_{cs}(t) + t.R_{data}(2(L_{packet} + L_{CTS} + L_{ack})t_{bit} + (K+1)T_{sp}) + (K+4)T_{SW} \end{aligned} \quad (10)$$

III.1.4 Proposed Next Sleep Interval Determination in E2A2S-WSN

E2A2S-WSN operates using a dynamic duty cycle adjusted according to each node's energy harvesting rate. Nodes with higher available energy remain active longer and thus forward more packets. To reduce collisions among neighboring nodes, the protocol assigns differentiated sleep durations that are intentionally non-uniform. Nodes with lower energy levels enter deeper sleep periods to harvest more energy and restore their balance. This section presents the mechanism used to determine the next sleep duration.

1. Node residual energy calculation

The residual energy of node i at time t ($E_{R_i}(t)$) equals the previous energy minus the consumed energy plus the harvested energy over the interval Δt .

$$E_{R_i}(t) = E_{R_i}(t - \Delta t) - E_{used_i}(\Delta t) + E_{harvested_i}(\Delta t) \quad (11)$$

Where:

$\Delta t = t - t_{prev}$ and t_{prev} represents the previous evaluation instant.

$E_{R_i}(t - \Delta t)$: residual energy of node i at the previous time instant.

$E_{used_i}(\Delta t)$: energy consumed by node i during the Δt .

$E_{harvested_i}(\Delta t)$: energy harvested by node i during the same interval Δt .

2. Node next sleep duration calculation

To compute the next sleep duration of each node i , E2A2S-WSN relies on two energy thresholds: a threshold energy E_{AL} and a critical energy E_{ML} , with $E_{MAX} > E_{AL} > E_{ML}$. E2A2S-WSN operates in two duty-cycle modes:

2.1. Fixed Mode

At network startup, each node follows administrator-defined sleep and wake durations. This mode is maintained as long as the residual energy remains greater than or equal to E_{AL} .

2.2. Dynamic Mode

When operating dynamically, the sleep duration is adjusted according to the node's residual energy. where this mode is used by each node i in the rest of its operation. The next sleep duration is calculated using the equations below

• Equation for calculating long sleep Duration.

$$D_{SLP_i}(E_{R_i}(t)) = \left(\frac{E_{Max} - E_{R_i}(t)}{E_{Max} - E_{AL}} \right) \times D_{SS_i} \quad (\text{When } D_{SS_i} \text{ is only computed}) \quad (12)$$

$$D_{SLP_i}(E_{R_i}(t)) = \left(\frac{E_{Max} - E_{R_i}(t)}{E_{Max} - E_{AL}} \right) \cdot D_{SS_i} + \mu(E_{R_i}(t)) \cdot \rho \quad (\text{When } D_{CSS_i} \text{ and } D_{SS_i} \text{ are computed}) \quad (13)$$

• Equation for calculating short sleep Duration.

$$D_{SLP_i}(E_{R_i}(t)) = e^{\log_2 \left(\frac{E_{Max} - E_{remi}}{E_{Max} - E_{Thr}} \right) \times D_{SS_i}} \quad (\text{When } D_{SS_i} \text{ is not calculated and } E_{R_i}(t) < E_{Max}) \quad (14)$$

(The old computed D_{SS_i} value is used)

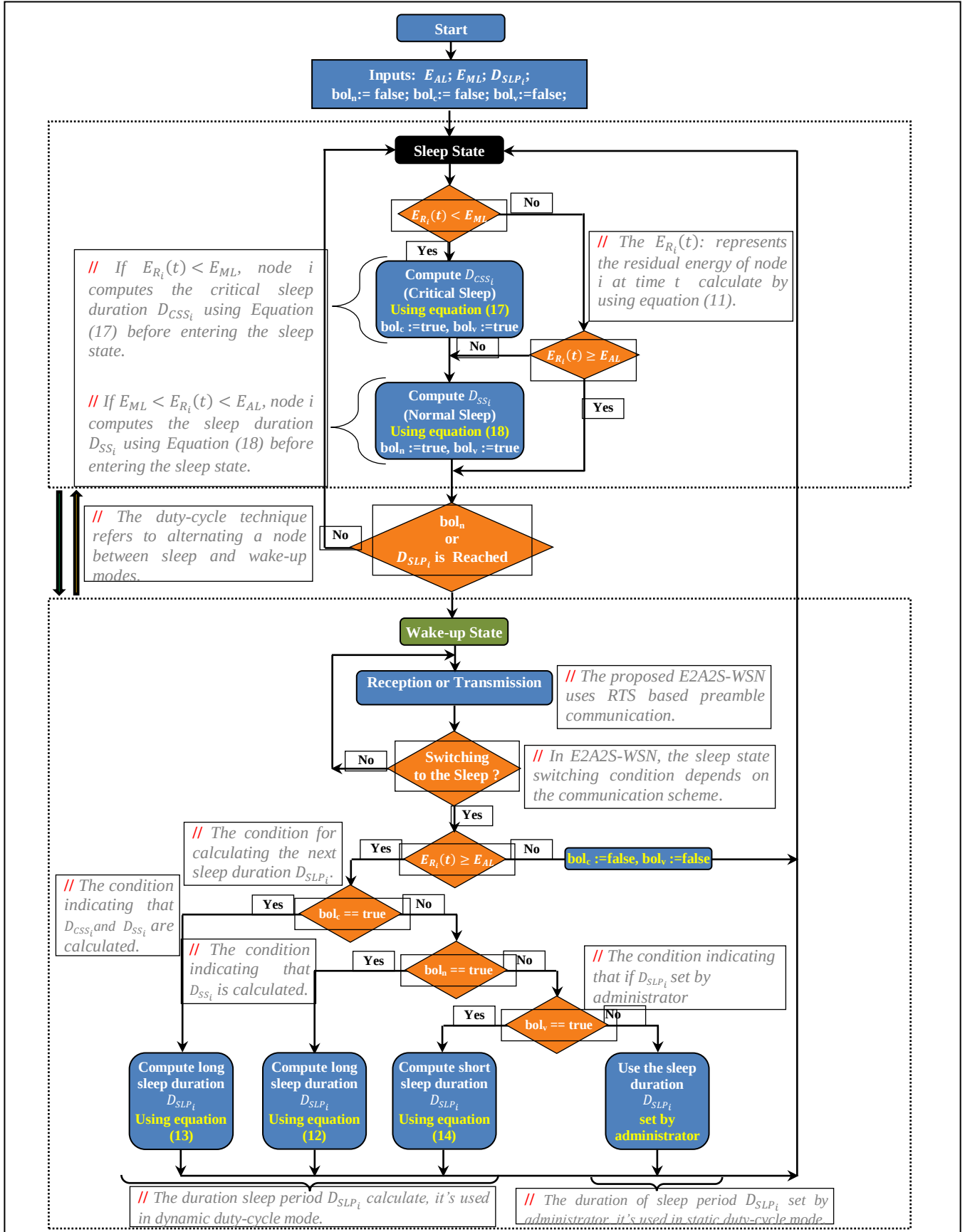


Figure 5: The key functions of the proposed E2A2S-WSN scheme.

Source: Author, (2026).

With:

$$\mu(E_{R_i}(t)) = \frac{(E_{R_i}(t) - E_{Max}) * (E_{R_i}(t) - E_{AL})}{E_{AL} - E_{ML}} \quad (15)$$

$$\rho = \left(\frac{D_{CSS_i}}{E_{Max} - E_{ML}} - \frac{D_{SS_i}}{E_{Max} - E_{AL}} \right) \quad (16)$$

$$D_{CSS_i} = \min(D_{CSS_i}, 1) \quad (17)$$

$$D_{SS_i} = \min(D_{SS_i}, 1) \quad (18)$$

Where:

$E_{R_i}(t)$: Residual energy of node i at t instant.

D_{SS_i} : Sleep duration of node i until its residual energy becomes greater than or equal to the threshold E_{AL} .

D_{CSS_i} : Critical sleep duration of node i until its residual energy becomes greater than or equal to the critical threshold E_{ML} .

2.3. Next sleep duration calculation procedure

The procedure for computing the next sleep duration $D_{SLP_i}(E_{R_i}(t))$ of node i in this mode is described below and is illustrated in Fig. 5.

a. In Sleep State

1. If $E_{R_i}(t) < E_{ML}$, node i first calculates the elapsed **critical sleep duration** D_{CSS_i} using Equation (17) until its residual energy reaches E_{ML} , and then computes the normal sleep duration D_{SS_i} using Equation (18) until its residual energy reaches E_{AL} .
2. If $E_{ML} < E_{R_i}(t) < E_{AL}$, node i computes only the elapsed normal sleep duration D_{SS_i} using Equation (18), until its residual energy reaches E_{AL} . This check is performed before entering the sleep state.

b. In wake-up State

1. **The long sleep duration calculation.** While $E_{R_i}(t) \geq E_{AL}$, node i computes its long sleep interval $D_{SLP_i}(E_{R_i}(t))$ as follows:
 - 1.1. Using Equation (12) if only D_{SS_i} has been calculated.
 - 1.2. Using Equation (13) if both D_{SS_i} and D_{CSS_i} have been calculated.

2. **The short sleep duration is computed** for node i while $E_{R_i}(t) \geq E_{AL}$ using Equation (14), with the node employing the previously calculated value of D_{SS_i} if it has not been computed yet.

III.2 SIMULATION

III.2.1 Implementation and Simulation in OMNeT++/MiXiM

The proposed E2A2S-WSN is implemented using the OMNeT++ simulator with the MiXiM framework [25], [26]. A custom node module, HostE2A2SWS, based on WirelessNodeBattery, is created, featuring standard layers (application, presentation, session, transport, network) and a custom network interface card (NIC) NicE2A2SWS integrating the new MAC module E2A2S-WSNLayer, which manages connections with other modules and layers.

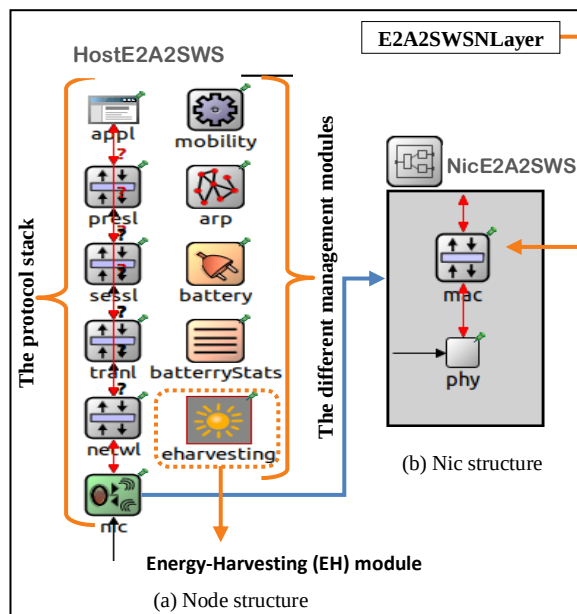


Figure 6: The architecture of the node and the NIC module employed in E2A2S-WSN for WSN implementation.
Source: Author, (2026).

Additional modules handle mobility, address resolution (ARP), battery management, energy statistics, and a new energy harvesting unit supporting exponential, uniform, or periodic harvesting. This architecture allows nodes to switch between sleep and active states and to transmit packets, facilitating performance evaluation of E2A2S-WSN. The structure of a node and the structure of the NIC module used in the WSN by E2A2S-WSN are illustrated in Figure 6.

III.2.2 Simulation Setup and Network Topology

To evaluate the proposed E2A2S-WSN scheme, a wireless sensor network was simulated using OMNeT++-4.6 with the MiXiM-2.3 framework.

Table 2: Parameters of simulation.

Parameter	Value
Nodes number	20, 40, 60, 80, 100
Simulation time/run	1000s
Playground Size	400x400 m ² , 600x600 m ² , 800x800 m ² , 950x950 m ² , 1100x1100 m ²
Mobility Type	ConstSpeedMobility
Mobility Speed	2 mps
Start residual energy $E_{R_i}(t)$	50 J
Allowed Level E_{AL}	30 J
Energy completion threshold	35 J
Safety margin α	5%
Minimum required Level E_{ML}	15 J
Load balancing Factor β	0.2
Traffic Type	Periodic
Traffic Param	0.1s, 0.5s
Number of Packets sent	500
Destination Node	19, 39, 59, 79, 99
Queue Size	10 packets
MaxAttempts	2
Battery capacity	100 J
Harvesting Type	Periodic
Harvesting Param	0.05 s
Harvesting rate randomly	[0mW...50mW]

Source: Author, (2026).

Simulation parameters, defined in the omnetpp.ini file, include the MAC type and physical layer settings. Two key intervals are considered: Traffic Param (time between packet transmissions) and Harvesting Param (time between energy harvesting events). Simulations involve 20 to 100 mobile sensor nodes deployed over areas ranging from 400×400 m² to 1100×1100 m², with 100 m spacing, during 1000 s of simulated time. Nodes generate periodic traffic (0.1 or 0.5 s) toward a sink via multi-hop communication. Energy harvesting is periodic (0.05 s), with harvested energy randomly varying between 0 and 50 mW. Each node starts with 50 J (maximum 100 J), with energy levels set to $E_{AL} = 30 J$, $E_{CTH} = 35 J$, and $E_{ML} = 15 J$. Table 2 displays the different parameters that were employed.

III.2.3 Performance Evaluation

The performance of the proposed E2A2S-WSN scheme is evaluated through extensive simulations and compared to a RDEHWSN scheme with a less adaptive duty-cycle. E2A2S-WSN ensures stable network operation by dynamically adjusting nodes' duty-cycles based on their estimated residual energy. The evaluation uses the following performance metrics:

Average Packet Latency (APL): The mean end-to-end delay experienced by successfully delivered packets. Lower APL indicates improved temporal efficiency.

Packet Delivery Ratio (PDR): Ratio of successfully received packets at the destination to the total packets transmitted by source nodes. This metric should be maximized to ensure reliable communication.

$$PDR = \frac{P_{received}}{P_{sent}} \quad (19)$$

Where:

$P_{received}$: Total number of packets successfully received at the sink node.

P_{sent} : Total number of packets generated and transmitted by the source nodes during the simulation.

Average Energy Consumption per Node: Defined as the average of the mean consumed energy (MCE) across all nodes in the WSN, and should be minimized:

$$Avg(MCE) = \frac{1}{N} \sum_{i=1}^N MCE_i \quad (20)$$

Where:

$$MCE_i = \frac{E_{consemed,i}}{T_{simulated\ time}} \quad (21)$$

With: $E_{consemed,i}$: consumed energy by the node i .

Network Lifetime (L): Defined as the time until the first sensor node depletes its energy or becomes unable to transmit during data collection. This metric should be maximized.

Throughput (THR): the total transfer rate (obtained bytes/ time of simulation), expressed in bits per second, which should be augmented. It can be calculated as:

$$THR = \frac{Nbr_{tran}^{pck} \times \text{size of packet}}{\text{simulation time}} \quad (22)$$

Where: Nbr_{tran}^{pck} : Number of transferred packets.

IV. RESULTS AND DISCUSSIONS

Figures 7–12 present the simulation results in terms of packet delivery ratio, average latency (ms), throughput (bps), average energy consumption per node (mJ), and network lifetime (s). The evaluation is conducted under different traffic scenarios, where the traffic parameter is set to 0.1 s or 0.5 s, the number of nodes varies from 20 to 100, and the total transmitted packets set to 500. The results show that increasing the number of nodes in the WSN leads to a decrease in packet delivery ratio, while most other metrics increase, including average latency, throughput, network lifetime, and overall energy consumption. The rise in energy consumption is further amplified by the increase in the number of transmitted packets.

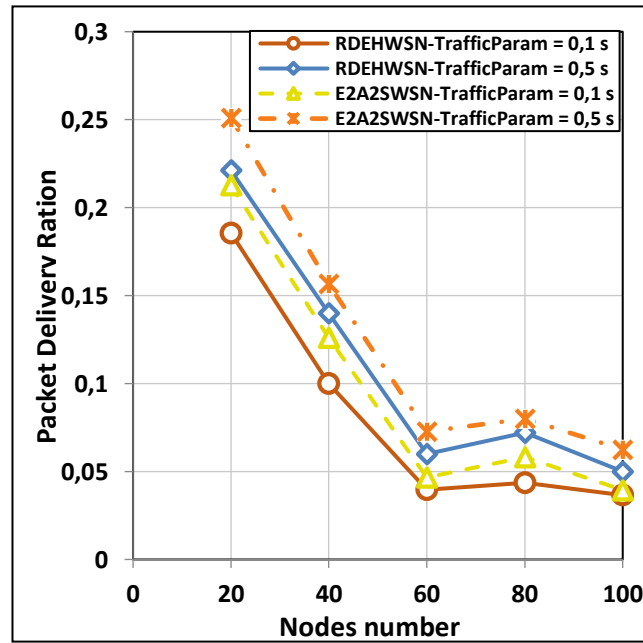


Figure 7: Packet Delivery Ration.
Source: Author, (2026).

In Figure 7, the E2A2SWSN outperforms the RDEHWSN in terms of packet delivery ratio across different EH rates. This improvement is mainly attributed to the more aggressive and fine-grained dynamic adjustment of the duty cycle in E2A2SWSN, which is driven by the residual energy that may progressively increase over time. In addition, the superior performance results from the integration of pulse-boot technology and the efficient load balancing mechanism implemented through the proposed relay node selection procedure. This mechanism ensures a better distribution of traffic among WSN nodes compared to RDEHWSN. Furthermore, in E2A2SWSN, sleep periods are intentionally adjusted with a higher incremental rate than in RDEHWSN, where sleep scheduling may not be symmetrical among neighboring nodes. This coordinated adjustment significantly reduces packet collisions and retransmissions. In contrast, in RDEHWSN, the redirection of data packets from the sender to the receiver can increase the likelihood of collisions, which in turn raises the probability of packet loss. These repeated retransmissions lead to higher energy consumption and may cause noticeable disruptions in WSN communication. For example, when the number of nodes increases from 20 to 60 (Figure 7), E2A2SWSN achieves higher packet delivery rates than RDEHWSN. At a traffic interval of 0.1 s, the improvement ranges from approximately 12.75% to 15.16%, while at 0.5 s, it varies between 11.95% and 17.49%. With 100 nodes, E2A2SWSN further demonstrates significant gains, improving the delivery rate by 7.45% at 0.1 s and 20.05% at 0.5 s compared to RDEHWSN. Overall, E2A2SWSN consistently provides better packet delivery performance than RDEHWSN, especially as WSN density increases.

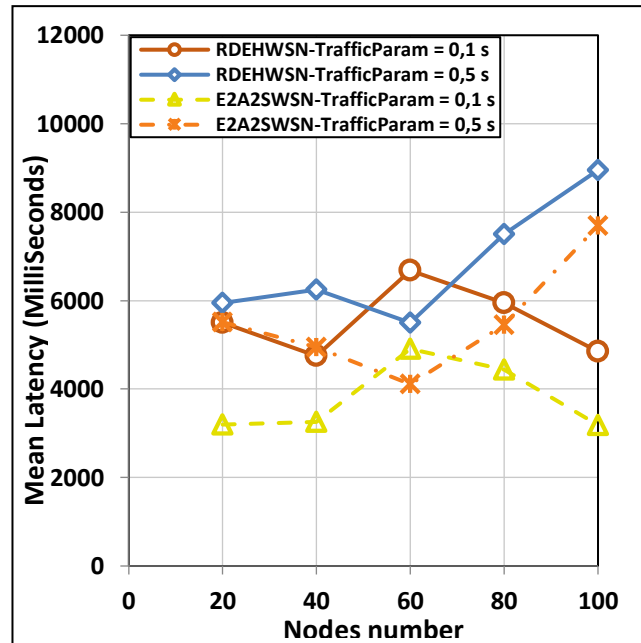


Figure 8: Mean Latency.
Source: Author, (2026).

Figure 8 shows that E2A2SWSN outperforms RDEHWSN as the number of nodes increases, particularly in terms of average latency. This improvement is mainly due to the relay node selection mechanism, which ensures efficient load balancing by prioritizing nodes with higher residual energy and shorter standby durations. The sleep time is dynamically computed according to the evolution of residual energy. In the case of a rapid increase in residual power, the short sleep time is calculated using equation (14), similarly to RDEHWSN. However, when the residual energy increases slowly, a long sleep time is determined using equations (12) or (13), which provide more accurate estimation than RDEHWSN. Moreover, the use of a discontinuous preamble reduces packet buffering and retransmissions, further decreasing latency. As a result, with 100 nodes, E2A2SWSN improves the average response time by approximately 34.27% at a traffic interval of 0.1 s and by 14.07% at 0.5 s compared to RDEHWSN.

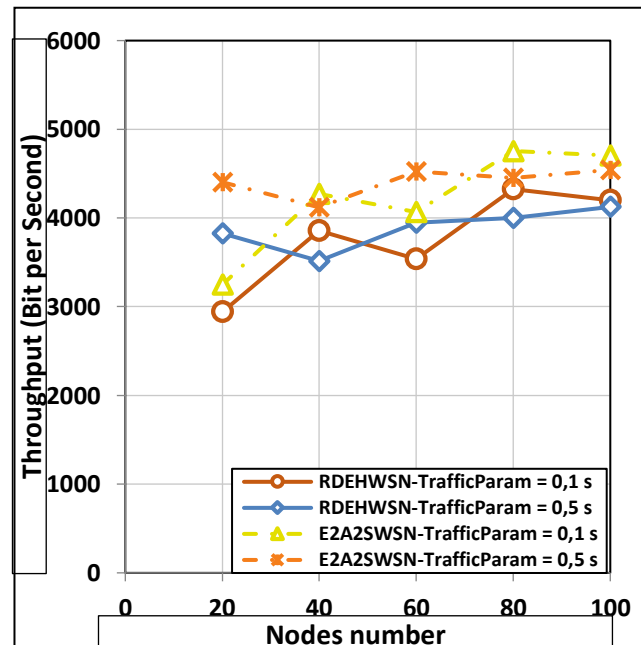


Figure 9: Throughput.
Source: Author, (2026).

Figure 9 shows that the E2A2SWSN network achieves higher throughput than RDEHWSN as the network size increases. This improvement is mainly attributed to the significant dynamic reduction of the sensor node activity period, which is adaptively adjusted according to the combined harvested and residual energy levels. Such an approach enables a more aggressive and precise duty-cycle adaptation compared to RDEHWSN. In addition, the use of an intermittent (discontinuous) preamble mechanism, combined with an efficient relay node selection strategy, ensures effective load balancing among nodes. This coordination reduces packet collisions and retransmissions. Since a higher collision rate increases transmission delay, packet loss, and energy consumption, minimizing retransmissions directly enhances throughput and stabilizes data transmission in the WSN.

For instance, when the number of nodes increases from 60 to 100 with a traffic interval of 0.1 s, Figure 9 indicates a throughput increase of 18.62% for E2A2SWSN, compared to 15.69% for RDEHWSN. Moreover, with 100 nodes and a traffic interval of 0.1 s, E2A2SWSN achieves an additional throughput gain of approximately 10.75% over RDEHWSN. Overall, E2A2SWSN provides more stable and efficient throughput performance.

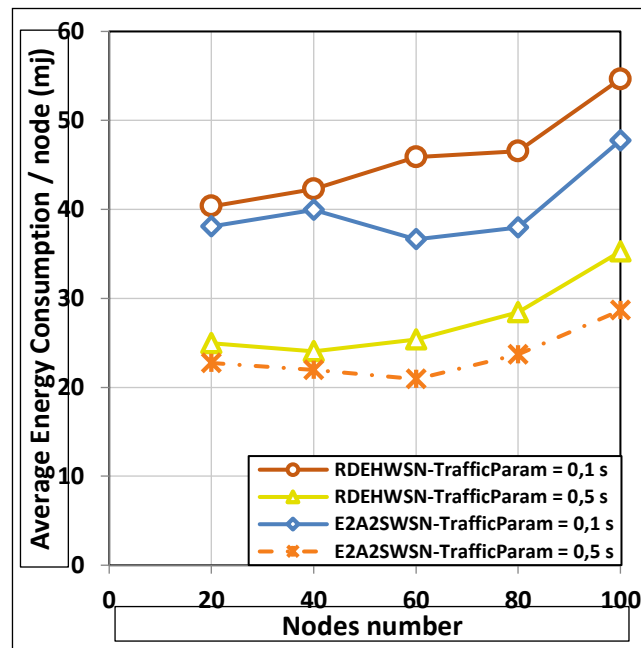


Figure 10: Average energy consumption.
Source: Author, (2026).

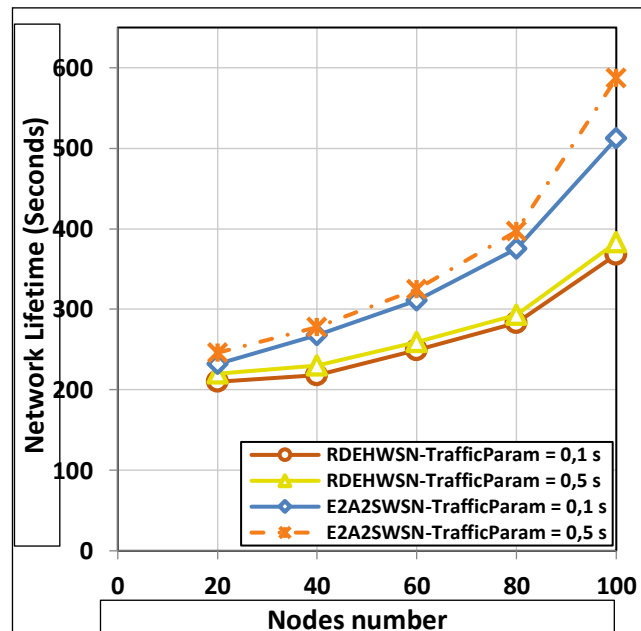


Figure 11: Network lifetime.
Source: Author, (2026).

Figure 10 shows that E2A2SWSN achieves better energy consumption performance than RDEHWSN under different energy harvesting (EH) rates. This improvement is mainly due to the intermittent booting mechanism, which allows each sensor node to dynamically and more accurately adjust its duty cycle based on the evolution of residual energy. As residual power increases over time, nodes can refine their operating and sleep periods more effectively than in RDEHWSN. Sleep durations are also carefully coordinated and are not necessarily identical among neighboring nodes, which helps reduce simultaneous wake-ups and channel contention. In addition, the efficient load balancing mechanism implemented through relay node selection minimizes packet collisions and retransmissions two major sources of excessive energy consumption and communication interruptions in WSNs. Figure 10 further indicates that, for traffic intervals of 0.1 s and 0.5 s, the energy-saving efficiency per node in E2A2SWSN remains consistently higher throughout the simulation compared to RDEHWSN. For example, at a traffic interval of 0.5 s, E2A2SWSN improves energy conservation by approximately 17.57% with 20 nodes and by about 18.77% with 100 nodes. Overall, E2A2SWSN ensures more efficient and scalable energy management.

The results related to the network lifetime metric indicate that the lifetime increases with the number of nodes for both E2A2SWSN and RDEHWSN under different EH rates. This improvement is mainly due to the use of the strobed preamble mechanism and the dynamic duty-cycle adaptation implemented in both schemes. As illustrated in Figure 11, E2A2SWSN outperforms RDEHWSN because it applies a more aggressive and in-depth dynamic adjustment of the duty cycle. Moreover, E2A2SWSN integrates a relay node selection mechanism that ensures efficient load balancing within the WSN. This strategy prioritizes nodes with higher residual energy, enabling them to remain active with shorter sleep durations, while preventing relay nodes from rapidly depleting their energy after cooperative transmissions. As a result, the overall network lifetime is significantly extended. Figure 11 further shows that when the number of nodes increases from 20 to 100, E2A2SWSN improves network lifetime by approximately 9.48% to 28.12% at a traffic interval of 0.1 s, and by 10.57% to 34.75% at 0.5 s, compared to RDEHWSN. To improve WSN performance in EH environments, particularly in terms of energy efficiency, mean latency, throughput, and packet delivery ratio, it is essential to ensure load balancing among nodes and to more aggressively reduce the duty cycle. This approach helps limit energy consumption caused by long active periods and collisions during data transmission, which are major sources of performance degradation, delays, and packet loss in WSNs. By combining load balancing with adaptive duty-cycle reduction, E2A2SWSN dynamically adjusts nodes' sleep periods so that neighboring nodes are unlikely to wake up simultaneously, thereby reducing collisions and retransmissions. As a result, E2A2SWSN outperforms RDEHWSN, which also uses a dynamic duty cycle but cannot guarantee effective load balancing and behaves similarly only when the average EH rate is high. Overall, E2A2SWSN achieves significant improvements in energy efficiency, throughput, mean latency, packet delivery ratio, and WSN lifetime compared with RDEHWSN.

V. CONCLUSIONS

This paper introduces the E2A2SWSN scheme for mobile EH-WSNs as an improved version of RDEHWSN. The proposed approach reduces energy consumption through dynamic duty-cycle scheduling combined with a strobed preamble mechanism and an effective load balancing strategy. Its main contribution is the accurate and more adaptive computation of the next sleep period based on residual energy, allowing each node to dynamically adjust its duty cycle according to the harvested energy rate. Furthermore, a novel relay node selection mechanism ensures balanced energy usage among nodes, prevents premature energy depletion, and maintains stable WSN operation. Simulation results under various traffic conditions and EH rates show that E2A2SWSN outperforms RDEHWSN by improving packet delivery ratio, reducing latency, increasing throughput, enhancing energy efficiency, and extending WSN lifetime. Future work will evaluate the scheme under additional traffic models and develop a DTN (Delay Tolerant Network) based algorithm to handle scenarios with a limited number of active nodes due to prolonged low EH or high dormancy levels.

VI. AUTHOR'S CONTRIBUTION

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