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RESEARCH ARTICLE

Energy-Efficient Deviation Aware Adaptive Bit-Mapping Medium Access Control Protocol for Wireless Sensor Network

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ABSTRACT In the present work, the energy-efficient medium access control protocol is proposed for wireless sensor network application. The proposed protocol involves efficient data transmission by removing redundant data. The deviation function is used for data filtration and energy-efficient data transmission with guarantee data consistency. The optimal number of slots is allotted to the sensor node based on the data sensitivity of the specific sensor. Therefore, the sensor-centric data sensitivity function is used for each individual sensor, and the adaptive data slot is allotted based on the requirement of the sensor node. The bit mapping approach is used to reserve the data slot. Prior approaches have not effectively addressed the dynamic allocation of transmission slots based on individual sensor data sensitivity. Therefore, the present work deals with a more adaptive and efficient protocol to optimize resource utilization and network performance. In the present work, the deviation-aware adaptive bit-mapping medium access control (DAABMA) protocol is proposed. The results are analyzed for various possible scenarios to prove the superiority of the proposed method.

INDEX TERMS Wireless sensor network, bit-map-assisted, energy-efficient, deviation aware, medium access control.

I. INTRODUCTION

The increasing demand for sensor data in different monitoring areas and other applications triggered the use of machine learning (ML), artificial intelligence (AI), or technologies that relate to them in our ordinary lives. As the range of available datasets increases, the importance of feature analysis and the utilization of AI/ML techniques has become paramount for model training, analysis, and decision-making across numerous application domains [1]. Machine learning is known to expose complicated patterns absent in large and noisy datasets, which is a strength when it comes to such fields as medical research [2] or biology where complicated data analysis is needed [1].

There is already extensive data being produced with the specific purpose of surrounding specific use cases. Illustrations have been made for activities like human activity understanding, basketball game activity recognition, violence detection, and sentiment analysis of social media posts [3], [4], [5], [6]. These datasets are very important for machine learning training and validation for precise forecasting [7] and analysis for their respective domains.

Integrating IoT and WSN with AI/ML models and real-time prediction [8] of crucial parameters are very important for many monitoring applications. Early prediction helps to avoid accidents or any misshaping. Therefore, nowadays,

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researchers and industries depend on the efficient deployment of WSN/IoT networks [9]. Such networks efficiently collect data from the monitoring field and transmit it to the headquarters or cloud. The sensor node is the primary unit that senses the data and transmits it to the sink node. In wireless sensor networks, the devices are mainly battery-operated, and they consume a lot of energy in data transmission. Therefore, energy-efficient and intelligent data transmission approach is primary requirement for such applications [10]. The researchers have proposed many protocols for energy-efficient data transmission. However, the intelligent reservation of the data slots can further reduce the energy consumption of the devices.

Now a days sensor nodes are very tiny and comes with a good computational and processing power capacity [11]. Therefore, sensor nodes are capable to take intelligent decision. In the present work, an intelligent approach is proposed for both data slot selection and efficient transmission of the data. The proposed method reserves a data slot based on the sensitivity of the data. The sensitivity of the data sample is decided based on the deviation with respect to the window of previous data sample transmission. This approach not only allows the removal of the redundant data at the sensor node but also reduces the overhead of the cluster head or sink node. In this way, the cluster head can manage more number of sensor nodes in a dense wireless sensor network. The details of the proposed method is discussed in the Section II and Section III.

The rest of the paper is organized as described in this section. Section II presents related work on adaptive BMA, and data consistency. Section III outlines the mathematical modeling and algorithm of the proposed research work. In Section IV, the simulation results are described considering various scenarios and evaluating metrics including transmission probability, packet size, and network density. In addition, the performance of the proposed method is compared with the performance of the existing methods, i.e. EABMA, and ABMA. Finally, Section V concludes the paper, summarizing the main findings and discussing future research directions.

II. RELATED WORK

There have been many efforts done by the researchers to improve MAC protocols and to enhance the overall QoS and Energy Consumption [12], [13]. The key concepts and the contributions of the researchers are discussed in this section. In [14], the traffic adaptive MAC protocol is proposed for the energy-efficient data transmission in wireless sensor network. The algorithm dynamically adjusts the duty cycle based on the varying data traffic levels. The authors have not addressed the scalability issue in dense sensor network.

For the efficient utilization of bandwidth, in [15], an error-adaptive MAC protocol is proposed for the efficient utilization of available spectrum bandwidth in cognitive radio networks. The protocol aims to enhance the throughput of cognitive radio devices by dynamically switching between error-recovery mode and dual-transmit mode based on the channel status. The proposed method addresses the issue of spectrum deficiency by effectively utilizing the randomly available spectrum resources in cognitive radio networks. The protocol allows the cognitive devices to use additional channels acquired from legacy networks for frame error recovery when the link status is poor. This method increases the throughput when the wireless medium is stable and reliable.

To further improve the performance, in [16], the authors proposed a priority-based adaptive MAC protocol (PM-MAC) for UAV ad hoc networks. The protocol deals with the challenges posed by UAV ad hoc networks, such as fast-moving nodes and frequent changes in network topology. The proposed PM-MAC protocol ensures access to high-priority packets in UAV ad hoc networks through several key mechanisms. In first method, the protocol classifies arriving packets into different priority queues and utilizes a Markov chain model to analyze the channel access probabilities of these queues. This ensures that packets with high priority have a higher probability of accessing the channel. In the second method, the protocol adaptively adjusts the size of the contention window based on back-off times and the current packet size, allowing for efficient and adaptive channel access.

In the above discussed papers, the researchers have focused high throughput reliable transmission in energy-efficient manner. For the uniform distribution of slots in adaptive data traffic condition, the researchers have proposed variants of TDMA MAC protocol for energy-efficient data transmission. In [17], the author has proposed an energy-efficient method to save sensor nodes' energy consumption. However, the author has not proposed any mechanism to save the energy consumption of cluster head nodes.

To overcome the issue, in [18], authors have proposed a bit mapping approach to reduce energy consumption using efficient allotment of data slots. However, the energy consumption of the contention period is very high in such protocols for highly dense networks. To overcome the issue, in [19], the author has used a piggybacking approach for the reservation of data slots. The EBMA MAC protocol is suitable for moderate data traffic applications but fails to perform optimally for high data traffic application due to lack of adaptation of slot duration in non-predictable data traffic applications.

In [20], the author has proposed small-sized time slots, employing a knapsack algorithm for slot scheduling to minimize packet delay and enhance link utilization. The short node addresses are introduced to reduce control overhead and improve energy efficiency. However, the proposed method has not addressed the dynamic data traffic condition. To overcome the drawback, in [21], the author has proposed an adaptive slot allotment method for low, moderate, and high data traffic applications.

In practical applications, sensors generate redundant data, and filtration of redundant data at the sensor node end is important to reduce the cluster's energy consumption and overhead. Many research works have reported the issue and proposed data aggregation and filtration methods to deal with data redundancy [22], [23], [24], [25], [26]. In [25], Shabna et al. proposed a Spatio-Temporal Correlation Algorithm (STCA), which efficiently removes redundant data transmission by reducing the sampling rate. STCA can be used for both event-driven and continuous monitoring of real-time applications, but it is only suitable for highly correlated scenarios. In [26], Kandukuri et al. proposed a novel algorithm called Data Aggregation Window Function (DAWF), which employs a Relative Variation (RV) based window function to efficiently reduce spatio-temporal redundancies in Wireless Sensor Networks (WSNs). DAWF includes a pre-filtration approach for redundant data filtration at each sensor node and can also be used for both event-driven and continuous monitoring. However, DAWF suffers from low aggregation efficiency. Thus, while both STCA and DAWF are valuable for reducing redundant data in specific contexts, STCA's suitability is limited to highly correlated scenarios, and DAWF's primary limitation is its low aggregation efficiency. In above two works [25], [26], author have not used any energy-efficient medium access control protocol. To overcome the issue, sunny et al. has proposed energy-efficient data-sensitive two layer MAC protocol (TLHA). The TLHA has a limitation in that it does not provide adaptive slot allotment based on dynamic data traffic. However, as previously discussed, [21] have proposed adaptive slot allotment method (ABMA- Adaptive bit-map assisted), yet it lacks data-sensitive aggregation.

Thus, to the best of our knowledge, a data-sensitive aware, energy-efficient, traffic-adaptive MAC protocol has not yet been reported for highly dense sensor networks. To address the issue, the present work has proposed an energy-efficient deviation-aware adaptive BMA (DAABMA) MAC protocol. The proposed approach uses adaptive slot allotment method. The proposed method precisely measures the slot requirement in each slot and utilizes the bandwidth in most efficient way. As the slot allotment is purely adaptive and based on the requirement of the sensor nodes, thus, the devices turns-on their radio in their allotted slot only. The proposed method reserves a data slot based on the sensitivity of the data. The sensitivity of the data sample is decided based on the deviation with respect to the window of previous data sample transmission. This approach not only allows the removal of the redundant data at the sensor node but also reduces the overhead of the cluster head or sink node.

The novelty and the contribution of the proposed work is explained below:

- An Energy-Efficient data sensitivity based deviation-aware approach is proposed for the adaptive bit-mapping assisted medium access control protocol to make it more energy-efficient without compromising with the data consistency.
- Unlike, the previous works, in the proposed method, the performance is analyzed for the individual sensors as well as combination of sensors.
- The performance of the proposed method is compared Energy-Efficient BMA (E-BMA), and adaptive BMA (ABMA) MAC protocols [19], [21].
- The mathematical model is developed for the proposed DAABMA MAC protocol, and modeling is compared with the existing MAC protocol.
- The performance of the DAABMA MAC protocol is analyzed in terms of energy consumption and packet size for important parameters, e.g., packet size, number of nodes, and transmission probability.

The methodology of the proposed protocol is discussed in the next section.

III. METHODOLOGY OF PROPOSED DAABMA PROTOCOL

The proposed DAABMA MAC protocol decreases the energy consumption by efficient and intelligent data filtration method. The proposed approach incorporates a sensor-centric data deviation method. The method determines the deviation of current reading with respect to the window of previously selected data sample. In addition, the proposed approach dynamically adapts the data traffic condition based on the deviation of the data samples and optimizes the energy usage. By utilizing the data aggregation and filtration techniques at the sensor node level, redundant data is minimized and overhead of cluster-head node reduces.

Let S_s represent the sensor data for the s-th sensor. For example, S_1 temperature data, S_2 humidity data, and so on. As given in Algorithm-1, the data sample is recorded by the sensor (Input data). Let μ_s represent the mean of the sensor data S_s for the window size of W_s previous samples. The mean value is estimated by the sensor node for the specific sensor readings of the previous samples as derived in Eq 1.

$$\mu_s = \frac{1}{W_s} \sum_{j=1}^{W_s} X_{sj} \tag{1}$$

The standard deviation and deviation threshold is estimated as given in Eq 2 and Eq 3. Let X_{sj} represent the j-th sample of sensor S_s and θ_s represent the deviation threshold for sensor S_s.

$$\sigma_s = \sqrt{\frac{1}{W_s} \sum_{j=1}^{W_s} (X_{sj} - \mu_s)^2} \tag{2}$$

$$\theta_s = \mu_s + k \cdot \sigma_s \tag{3}$$

To derive the transmission probability of the sensor data using a Bernoulli random process, we can define a binary random variable that represents whether a sample is transmitted or not. Let's denote this random variable as T_{sj}, where s represents the sensor index and j represents the sample index. The transmission probability p_{sj} for each sample X_{sj} can be derived using a Bernoulli random variable, where: p_{sj} is the probability of transmission for sample X_{sj}. Similarly, $1 - p_{sj}$ is the probability of no transmission for sample X_{sj}. The transmission probability p_{sj} can be calculated

Algorithm 1 Deviation-Aware Adaptive Bit-Mapping Medium Access Control Protocol

Input
Sensor data S_s

Intermediate Parameters
Mean μ_s as given in Eq. 1
Standard Deviation σ_s as given in Eq. 2
Deviation Threshold θ_s as given in Eq. 3
Transmission Probability Parameter p_s as derived in Eq. 7

Output: Allocation of transmission slots based on individual sensor data sensitivity

Define network parameters and constraints
Initialize slot allocation variables
$\mu_s = \text{Mean}(S_s)$
$\sigma_s = \text{StandardDeviation}(S_s)$
$\theta_s = \mu_s + k \cdot \sigma_s$
$p_s = \text{CalculateTransmissionProbability}(S_s, \theta_s)$

```
foreach sensor node s in the network do
    foreach sample X_sj in sensor data S_s do
        if X_sj ≥ θ_s then
            Transmit sample X_sj
            AllocateDataSlot(X_sj) using AdaptiveBitMapAssistedApproach
        end
        p_sj = CalculateTransmissionProbability(X_sj, θ_s, p_s)
    end
end
while Communication continues do
    Monitor network status and sensor data  if Network conditions change then
        Update θ_s and p_s
        Adjust slot allocation accordingly
        Energy Consumption is estimated as given in Eq. 10.
    end
end
```

based on whether the sample X_{sj} exceeds the deviation threshold θ_i. If $X_{sj} > \theta_s$, then $T_{sj} = 1$ (transmitted), otherwise $T_{sj} = 0$ (not transmitted). The T_{sj} can be expressed as:

$$T_{sj} = \begin{cases} 1, & \text{if } X_{sj} > \theta_s \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

The transmission probability p_{sj} can be defined as:

$$p_{sj} = P(T_{sj} = 1) = P(X_{sj} > \theta_s) \tag{5}$$

Here, p_{sj} is the probability that the sample X_{sj} exceeds the deviation threshold θ_s, which depends on the distribution of the sensor data X_{sj}. If the sensor data X_{sj} follows a normal distribution, we can use the cumulative distribution function (CDF) of the normal distribution to calculate p_{sj}. For example, if X_{sj} follows a normal distribution with mean μ_s and standard deviation σ_s, then:

$$p_{sj} = P(X_{sj} > \theta_s) = 1 - \Phi\left(\frac{\theta_s - \mu_s}{\sigma_s}\right) \tag{6}$$

Here Φ is the standard normal CDF. The transmission probability can be defined for the s-th sensor node as p_s. Each sensor node independently decides whether to transmit a sample based on its own transmission probability p_s. The Bernoulli probability distribution is characterized by a parameter p_s, which represents the probability of success (transmission) for each trial. Therefore, the transmission probability p_{sj} for each sample X_{sj} of the s-th sensor node can be represented as given in Eq 7:

$$p_{sj} = p_s \tag{7}$$

This implies that each sample from the s-th sensor node has different transmission probability but overall average of transmission probability is p_s, which is constant for all samples of that sensor node. In a Bernoulli random process, the mean probability remains constant for overall trials, and the trials are independent of each other. Therefore, the overall transmission probability for each sample X_{sj} of the s-th sensor node remains the same throughout the process, and it is determined solely by the transmission probability parameter p_s.

In the proposed model, the utilization of probabilistic transmissions, as defined by the transmission probabilities in Eq. 5, indeed aims to optimize energy consumption while maintaining the integrity of data aggregation. The data samples will not be transmitted if the deviation of the data is very small with respect to the previous readings. The threshold is very small, which ensures that the data is redundant data and does not need to be transmitted. In this case, the receiver assumes that the current reading is equal to the previous reading and, hence, is not considered lost data. By dynamically adjusting transmission probabilities based on deviation thresholds, our model seeks to strike a balance between energy efficiency and data accuracy. The proposed model employs a sliding window approach, as described in Eq. 1, to continually update the deviation threshold based on the mean and standard deviation of the sensor data within a specific window size. This adaptive nature ensures that the deviation threshold remains relevant and reflective of the current sensor data distribution, thereby enhancing the accuracy of aggregated data.

The mathematical model of the proposed protocol is discussed in this section, and it is compared with the existing models. All the notations are given in Table. 1. In the proposed work, the mathematical model is developed for DAABMA and compared with regenerated mathematical models of E-BMA, and ABMA MAC protocols. As already discussed and reported in [19], the EBMA protocol uses piggybacking to save the energy of the sensor nodes for

TABLE 1. Symbol and parameters/quantity notation.

Symbol	Parameter/Quantity
N_s	Total No. of nodes in Cluster excluding CH
S	Total different types of of sensors
n_{s0k}	Count of nodes not piggybacked in E-BMA in k^{th} session
n_{sk}	count of source nodes in k^{th} session
n_{SN}	Temporary variable to count source node
μ_s	Mean value of the sensor data for the window size of W_s previous samples
σ_s	The standard deviation value of the sensor data for the window size of W_s previous samples
T_{sj}	Transmission parameter of sensor data
p_{sj}	Transmission probability of each sample X_{sj}
θ_s	Deviation Threshold
Po_t	Power consumption to transmit data
Po_r	Power consumption to receive data
Po_i	Power consumption during Idle mode
Po_e	Power Consumption during buffer check
T_d	Time duration of Data slot
T_c	Time duration of Control slot
T_{ch}	Broadcast slot time of Cluster-Head
T_e	Required time to checking buffer
n_{s1k}	Count of nodes generate one data packet in ABMA and DAABMA in k^{th} session
n_{s2k}	Count of nodes generate two data packets in ABMA and DAABMA in k^{th}
n_{s3k}	Count of nodes generate more than two data packets and DAABMA in k^{th}
K	Count of Sessions per frame
F	Count of frames in simulation duration
CP_{ijk}	Sensor node status during contention period for i^{th} node in j^{th} frame and k^{th} session, here 1 shows ON during else OFF
BS_{ijk}	Buffer status
B_{ijk}	Count of data packets in Buffer

utilization of slots and to save energy consumption in contention slots. The energy consumption equation of EBMA MAC protocol is derived in [21]. In EBMA protocol, non-source nodes employ a distinct radio usage strategy compared to the traditional BMA during a session. Throughout the session, non-source nodes in EBMA keep their radios deactivated entirely, which stands in contrast to their behavior in BMA. In EBMA, source nodes only transmit a control message during their designated contention slot, unless the channel has already been reserved by the same source node in the preceding frame's data packet. This approach effectively utilizes the idle state of non-source nodes.

Source nodes in E-BMA employ piggybacking to reserve data slots for subsequent sessions during the ongoing session. Consequently, if a source node has already secured a channel by piggybacking a reservation in the prior data slot, it switches off its radio during the appropriate contention slot. This strategy optimizes energy consumption in E-BMA, leading to potential energy savings. The operation of steady state phase is divided into contention period and data transmission period. Therefore, overall energy consumption is sum of energy consumption during contention period and data transmission period, i.e., $EC_{E-BMA} = EC^{CP}_{E-BMA} + EC^{DTP}_{E-BMA}$. In contention period, the sensor nodes transmits the data to the CH node and at the end of the contention period, CH node broadcasts a control packet to all the SNs. To derive the energy consumption of contention period, the equation is divided into 3 main components, i.e., 1) energy consumed by SN's for transmission of control packets to CH node (EC^{SN}_{E-BMA}), 2) CH energy consumption for receiving data packet (EC^{CH}_{E-BMA}), 3) Energy Consumption in broadcasting control packet (slot allotment) by CH node to all the SN's ($EC^{Broadcast}_{E-BMA}$).Thus, the energy consumption of contention period is given below:

$$EC^{CP}_{E-BMA} = EC^{SN}_{E-BMA} + EC^{CH}_{E-BMA} + EC^{Broadcast}_{E-BMA} \quad (8)$$

The equation of sensor node energy consumption during contention period is given below. In this equation, $\sum_{s=1}^{S} n_{s0k} Po_t T_c$ is energy consumption in transmitting packet by non-piggybacking source nodes. The term Po_t represents the energy consumed when a sensor node (SN) device actively transmits a control packet, multiplied by the time T_c for which the channel is actively used for control packet transmission. Similarly, Po_r represents the energy consumed when cluster head (CH) node are in the receiving state. $\sum_{s=1}^{S} n_{s0k}(\sum_{s=1}^{S} N_s - 1) Po_i T_c$ is energy consumption by non-source nodes, and $\left(\sum_{s=1}^{S} N_s - \sum_{s=1}^{S} n_{s0k}\right) Po_i T_c$ is energy consumption by piggybacked nodes. Here, Po_i is idle state power consumption.

$$EC^{SN}_{E-BMA} = \sum_{s=1}^{S} n_{s0k} Po_t T_c + \sum_{s=1}^{S} n_{s0k} (\sum_{s=1}^{S} N_s - 1) Po_i T_c + \left(\sum_{s=1}^{S} N_s - \sum_{s=1}^{S} n_{s0k}\right) Po_i T_c \quad (9)$$

The second component (EC^{CH}_{E-BMA}) of contention period energy consumption is given below. In this component, CH node receives control packet transmitted by the SNs.

$$EC_{E-BMA}^{CH} = \sum_{s=1}^{S} n_{s0k} Po_r T_c \tag{10}$$

The third component ($EC_{E-BMA}^{Broadcast}$) of contention period energy consumption is given below. In the given equation, the first component ($Po_t T_{ch}$) is energy consumption of CH node due transmission of data packet from CH node to SN. The second component is energy consumption of SNs.

$$EC_{E-BMA}^{Broadcast} = Po_t T_{ch} + \sum_{s=1}^{S} N_s Po_r T_{ch} \tag{11}$$

The overall contention period energy consumption (EC_{E-BMA}^{CP}) as given below in Eq. 12 is sum of Eq. 9, Eq. 10, and Eq. 11.

$$\begin{aligned} EC_{E-BMA}^{CP} &= EC_{E-BMA}^{SN} + EC_{E-BMA}^{CH} + EC_{E-BMA}^{Broadcast} \\ &= \sum_{s=1}^{S} n_{s0k} Po_t T_c + \sum_{s=1}^{S} n_{s0k} (\sum_{s=1}^{S} N_s - 1) Po_i T_c \\ &\quad + \left(\sum_{s=1}^{S} N_s - \sum_{s=1}^{S} n_{s0k} \right) Po_i T_c \\ &\quad + \sum_{s=1}^{S} n_{s0k} Po_r T_c + + Po_t T_{ch} + \sum_{s=1}^{S} N_s Po_r T_{ch} \end{aligned} \tag{12}$$

The energy consumption for the data transmission period expression for E-BMA is given below. During data transmission period, each individual SN transmits the data to the CH node during their allotted time slot and all other SNs remains in sleep mode. Thus the total energy consumption by the source nodes and CH node, can be expressed as given in Eq. 13 below.

$$EC_{E-BMA}^{DTP} = \sum_{s=1}^{S} n_{sk} Po_t T_d + \sum_{s=1}^{S} n_{sk} Po_r T_d \tag{13}$$

As already discussed, in E-BMA, non-source nodes manage their radio usage differently than in BMA during a session. All non-source nodes in E-BMA keep their radios off throughout the whole session. Unless the channel has been reserved by the same source node in the previous frame's data packet, source nodes in E-BMA transmit a control message during their allotted contention slot. This phase involves the idle state of non-source nodes. Source nodes utilize piggybacking to reserve data slots for the subsequent session during the current session. This indicates that a source node turns off its radio during the appropriate contention slot if it has previously piggybacked a reservation in the prior data slot because it has already secured a channel. In this way, E-BMA saves energy and the total sum of energy consumption is sum of contention period energy consumption (Eq. 12) and data transmission period (Eq. 13). The energy consumption expression for K sessions of E-BMA is given below Eq. 14 [19], [21]:

$$\begin{aligned} &EC_{E-BMA} \\ &= EC_{E-BMA}^{CP} + EC_{E-BMA}^{DTP} \\ &= \Bigg(\sum_{s=1}^{S} n_{s0k} Po_t T_c + \sum_{s=1}^{S} n_{s0k} (\sum_{s=1}^{S} N_s - 1) Po_i T_c \\ &\quad + \sum_{s=1}^{S} N_s Po_r T_{ch} + \sum_{s=1}^{S} n_{s0k} Po_r T_c + \left(\sum_{s=1}^{S} N_s - \sum_{s=1}^{S} n_{s0k} \right) \\ &\quad \times Po_i T_c + Po_t T_{ch} + \sum_{s=1}^{S} n_{sk} Po_t T_d + \sum_{s=1}^{S} n_{sk} Po_r T_d \Bigg) K \end{aligned} \tag{14}$$

ABMA protocol functions in a manner closely resembling E-BMA. In ABMA, all source nodes that have reserved the channel either through a control slot or by piggybacking transmit their data. Meanwhile, all other nodes remain in a sleep state. The assignment of data slots in ABMA is based on the buffer status of nodes, which is transmitted in the control field of the contention slot. It is assumed that n_{s1k}, n_{s2k}, and n_{s3k} are number of nodes have reserved one, two, and three data slots of s^{th} sensor, respectively, based on their filled buffer status. Here, $n_s k = n_{s1k} + n_{s2k} + n_{s3k}$ and $(N_s - n_{sk})$ nodes are non-source nodes. The contention period energy consumption, data transmission period energy consumption, and overall energy consumption of ABMA is given below in Eq. 15, 16, 17, respectively [21]:

$$\begin{aligned} EC_{\text{ABMA}}^{CP} &= \sum_{s=1}^{S} n_{s0\ k} \left(Po_t T_c + (\sum_{s=1}^{S} N_s - 1) Po_i T_c \right) \\ &\quad + \sum_{s=1}^{S} N_s Po_r T_{ch} + \sum_{s=1}^{S} n_{s0\ k} Po_r T_c \\ &\quad + \left(\sum_{s=1}^{S} N_s - \sum_{s=1}^{S} n_{s0\ k} \right) Po_i T_c + Po_t T_{ch} \end{aligned} \tag{15}$$

$$\begin{aligned} EC_{\text{ABMA}}^{DTP} &= \sum_{s=1}^{S} n_{s1k} Po_t T_d + \sum_{s=1}^{S} n_{s1k} Po_r T_d \\ &\quad + \sum_{s=1}^{S} n_{s2k} Po_t\ (2T_d) + \sum_{s=1}^{S} n_{s2k} Po_r\ (2T_d) \\ &\quad + \sum_{s=1}^{S} n_{s3k} Po_t\ (3T_d) + \sum_{s=1}^{S} n_{s3k} Po_r\ (3T_d) \end{aligned} \tag{16}$$

Eq. 15 for contention period is almost similar to the Eq. 12 of EBMA contention period. The only change is their in data transmission period. In the data transmission period, the variable slots are allotted based on data traffic requirement. Thus, the data transmission period energy consumption can be expressed as sum of number of one data slot energy consumption ($\sum_{s=1}^{S} n_{s1k} Po_t T_d + \sum_{s=1}^{S} n_{s1k} Po_r T_d$), number of two data slot energy consumption ($\sum_{s=1}^{S} n_{s2k} Po_t (2T_d) +$

$\sum_{s=1}^{S} n_{s2k}Po_r(2T_d)$), and number of three data slot energy consumption ($\sum_{s=1}^{S} n_{s3k}Po_t(3T_d)$ + $\sum_{s=1}^{S} n_{s3k}Po_r(3T_d)$). The data transmission period energy consumption is given in Eq. 16.

The overall energy consumption is sum of contention period and data transmission period energy consumption as given in Eq. 17.

In the proposed deviation aware MAC protocol, the data slots are allotted based on the actual data traffic after filtration. For the redundant data removal, the deviation-aware approach is used as already discussed in Eq. 1 to Eq. 6. The estimated overall transmission probability is derived in Eq. 7. The overall transmitted packets and total energy consumption depend upon transmission probability. Thus, the actual generated data packets can be estimated based on Eq 7. The energy consumption expression for the DAABMA protocol, denoted as EC_{DAABMA}, which consist of various energy consumption components for contention period (EC^{CP}_{DAABMA}) as well as transmission period (EC^{DTP}_{DAABMA}). The energy consumption of contention period is given below in Eq. 18:

$$\begin{aligned} EC_{\text{ABMA}} &= EC^{CP}_{ABMA} + EC^{DTP}_{ABMA} \\ &= \Bigg(\sum_{s=1}^{S} n_{s0k}\Bigg(Po_tT_c + (\sum_{s=1}^{S} N_s - 1)Po_iT_c\Bigg) \\ &\quad + \sum_{s=1}^{S} N_sPo_rT_{ch} + \sum_{s=1}^{S} n_{s0k}Po_rT_c \\ &\quad + \Bigg(\sum_{s=1}^{S} N_s - \sum_{s=1}^{S} n_{s0k}\Bigg)Po_iT_c + Po_tT_{ch} \\ &\quad + \sum_{s=1}^{S} n_{s1k}Po_tT_d + \sum_{s=1}^{S} n_{s1k}Po_rT_d \\ &\quad + \sum_{s=1}^{S} n_{s2k}Po_t\ (2T_d) + \sum_{s=1}^{S} n_{s2k}Po_r\ (2T_d) \\ &\quad + \sum_{s=1}^{S} n_{s3k}Po_t\ (3T_d) + \sum_{s=1}^{S} n_{s3k}Po_r\ (3T_d)\Bigg)K \end{aligned} \tag{17}$$

$$\begin{aligned} EC^{CP}_{DAABMA} &= \sum_{s=1}^{S} p_sn_{s0k}\Bigg(Po_tT_c + (\sum_{s=1}^{S} N_s - 1)Po_iT_c\Bigg) \\ &\quad + \sum_{s=1}^{S} N_sPo_rT_{ch} + \sum_{s=1}^{S} p_sn_{s0k}Po_rT_c \\ &\quad + \Bigg(\sum_{s=1}^{S} N_s - \sum_{s=1}^{S} p_sn_{s0k}\Bigg)Po_iT_c + Po_tT_{ch} \end{aligned} \tag{18}$$

Firstly, the term p_sn_{s0k} denotes the actual generation of data traffic by the source node does not utilize piggybacking in DAABMA for the k^{th} session. Here, p_s is data transmission probability and as per the proposed algorithm, the data is transmitted only when deviation is more than the predefined threshold. This term is multiplied by the energy consumption during control slot transmission, Po_tT_c. Additionally, it accounts for the sum of idle power consumption, Po_i, during control slot transmission for all sensors except one sensor. Furthermore,, overall sensor nodes denoted by N_s, which consume energy Po_rT_{ch} during the cluster-head broadcast slot time T_{ch}. Moreover, cluster head receives data and during the receiving state for sensor s, the energy consumption is $p_sn_{s0k}Po_rT_c$.

The energy consumption during data slot transmission and reception for each scenario is derived below in Eq. 19 based on actual data traffic after removal of redundancy. Po_t and Po_r representing the power consumption for transmission and reception of the data packet with duration T_d,

$$\begin{aligned} &EC^{DTP}_{DAABMA} \\ &= \sum_{s=1}^{S} p_sn_{s1k}Po_tT_d + \sum_{s=1}^{S} p_sn_{s1k}Po_rT_d + \sum_{s=1}^{S} p_sn_{s2k}Po_t\ (2T_d) \\ &\quad + \sum_{s=1}^{S} p_sn_{s2k}Po_r\ (2T_d) + \sum_{s=1}^{S} p_sn_{s3k}Po_t\ (3T_d) \\ &\quad + \sum_{s=1}^{S} p_sn_{s3k}Po_r\ (3T_d) \end{aligned} \tag{19}$$

The overall energy consumption is then computed by summing up these contributions across all sensors s over K sessions. Additionally, contributions from source nodes generating one, two, and more than two data packets are considered. The data transmission equation of DAABMA (Eq. 19) is similar to the data transmission equation of ABMA (16). Finally, the total energy consumption is multiplied by the number of sessions per frame, K, to obtain the overall energy consumption for DAABMA as given below in Eq. 20.

$$\begin{aligned} &EC_{\text{DAABMA}} \\ &= \Bigg(\sum_{s=1}^{S} p_sn_{s0k}\Bigg(Po_tT_c + (\sum_{s=1}^{S} N_s - 1)Po_iT_c\Bigg) \\ &\quad + \sum_{s=1}^{S} N_sPo_rT_{ch} + \sum_{s=1}^{S} p_sn_{s0k}Po_rT_c \\ &\quad + \Bigg(\sum_{s=1}^{S} N_s - \sum_{s=1}^{S} p_sn_{s0k}\Bigg)Po_iT_c + Po_tT_{ch} \\ &\quad + \sum_{s=1}^{S} p_sn_{s1k}Po_tT_d + \sum_{s=1}^{S} p_sn_{s1k}Po_rT_d \\ &\quad + \sum_{s=1}^{S} p_sn_{s2k}Po_t\ (2T_d) + \sum_{s=1}^{S} p_sn_{s2k}Po_r\ (2T_d) \\ &\quad + \sum_{s=1}^{S} p_sn_{s3k}Po_t\ (3T_d) + \sum_{s=1}^{S} p_sn_{s3k}Po_r\ (3T_d)\Bigg)K \end{aligned} \tag{20}$$

TABLE 2. Sample data of various sensors [27].

Time	Temp	Hum	x	y	z
24-08-2021 10:19	76	16	-0.184	0.988	-0.068
24-08-2021 10:19	76	16	-0.184	0.984	-0.064
24-08-2021 10:19	76	16	-0.188	0.984	-0.064
24-08-2021 10:19	76	16	-0.184	0.984	-0.068
24-08-2021 10:19	76	16	-0.188	0.984	-0.072
24-08-2021 10:19	76	16	-0.18	0.996	-0.064
24-08-2021 10:19	76	16	-0.188	0.988	-0.052
24-08-2021 10:19	76	16	-0.188	0.996	-0.072
24-08-2021 10:19	76	16	-0.196	0.988	-0.06
24-08-2021 10:19	76	16	-0.188	0.988	-0.064
24-08-2021 10:20	76	16	-0.184	0.98	-0.068
24-08-2021 10:20	76	16	-0.188	0.984	-0.072
24-08-2021 10:20	76	16	-0.184	0.984	-0.06

The analytical model is used for the result analysis of the proposed DAABMA MAC protocol. The performance of the proposed model is compared with the existing models.

IV. RESULT AND DISCUSSION

In the present work, the proposed method is analyzed for the actual data traffic generated in railway application for the efficient monitoring as EBMA [19] MAC protocol is developed for the railway application. For the analysis of the proposed method, time instant data samples are used for various senors, e.g., temperature, humidity, accelerometer as given in [27]. The example of the data samples are given in Table. 2. The data samples are processed for the estimation of deviation threshold. The overall average deviation threshold is also estimated for 2500 samples for 3 sensors at 5 different locations. Average number of transmitted samples (out of 2500 samples), transmission probability of the individual sensor and overall sensors are estimated as given in Table. 3.

The estimated transmission probability plays a critical role in determining the overall energy consumption of a wireless sensor network. In this study, we have evaluated the performance of the proposed method, DAABMA, by comparing it with existing methods, namely E-BMA and ABMA, using the same simulation environment background and parameters. Data traffic for sensor nodes is generated based on a dataset provided in [27]. The simulation duration is 500 seconds, with 10 sessions per frame (denoted as $K = 10$). To ensure precise estimation of data traffic, 2500 samples are utilized for each sensor to estimate transmission probability of individual. MATLAB is employed as the simulator for the analysis. We utilize a 2.4 GHz mote module equipped with a CC2420 radio to analyze energy usage. Specifically, 50 mW is allocated for transmission, 54 mW for reception, and 50 mW for standby listening mode. Assuming a worst-case scenario, the practical data rate is set at 25 kb/s (assumed value), while the control packet size is fixed at 5 Bytes. Our performance analysis comprises two scenarios: firstly, evaluating network performance with varying numbers of nodes, both individually per sensor and collectively across all sensors, and secondly, assessing network performance with varying packet sizes, again considering both individual sensors and all sensors combined.

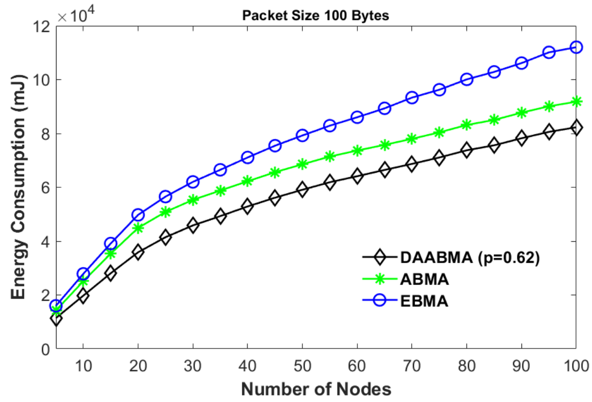

FIGURE 1. Energy consumption (in mW) vs number of nodes (S_1 temperature sensor).

A. SCENARIO-1(NUMBER OF NODES)

In this scenario, the performance of the proposed protocol and other existing protocols is analyzed for two different cases. First we have analyzed the variation of individual sensor nodes. In the first case, the number of sensor S_1 is varied 5 to 100. The packet size is 100 bytes, and the overall transmission probability after aggregation for sensor S_1 is approximately 0.62. All other parameters details are given in Table. 4.

The result is shown in Fig. 1 for variation of number of sensor (S_1). DAABMA shows superior performance in terms of energy consumption as compared to EBMA and ABMA across a range of node counts from 5 to 100. As the number of nodes increases, DAABMA consistently exhibits lower energy consumption compared to EBMA and ABMA. Overall, DAABMA achieves significant energy savings, with percentage reductions in energy consumption ranging from approximately 36% to 42% compared to EBMA, and approximately 11% to 24% compared to ABMA across the range of node counts analyzed. The energy savings observed in the DAABMA MAC protocol are mainly due to its probabilistic transmission mechanism, which only transmits data when deviations from previous readings exceed dynamically adjusted thresholds. This minimizes redundant transmissions, conserving energy. The sensor-based aggregation-aware protocol precisely checks the deviation in the readings and removes the redundant data. The removal of the redundant data reduces the total number of transmissions and saves energy. This proves the effectiveness of DAABMA in optimizing energy consumption in wireless sensor networks.

As per the analysis shown in Table. 3, the transmission probability of sensor S_1 (Temperature Sensor) is very high because there is large deviation in temperature samples. Although, the transmission probability dynamically changes based on deviation with respect to mean and window function, however, the overall transmission probability can be estimated based on the mean value of overall transmission probability because it follows Bernoulli distribution. Thus, the energy consumption can be estimated based on mean transmission probability.

TABLE 3. Transmission probability estimation of sensor data samples.

	Temperature	Humidity	Accelerometer		
			X	Y	Z
Location 1	1550	66	137	128	126
Location 2	1686	16	1123	1161	1150
Location 3	1373	18	1129	1207	1134
Location 4	1684	12	1155	1170	1167
Location 5	1413	14	1102	1160	1128
Average Transmitted Samples	1541.2	25.2	929.2	965.2	941
Transmission Probability of Individual Sensor	0.61648	0.01008	0.37168	0.38608	0.3764
Transmission Probability of overall sensors	0.352144				

TABLE 4. Parameter values.

Parameter	Value
Sim_Time	500 seconds
Ns1	Individual: 5 to 100, Combined 20
Ns2	Individual: 5 to 100, Combined 20
Ns3	Individual: 5 to 100, Combined 60
N	5 to 100
Tch	0.0032 seconds
Td	0.03125 seconds
Tc	0.0016 seconds
Pt	0.05 (Tx power in W)
Pr	0.054 (Rx Power in W)
Pe	0.05 (Power demand to check buffer status in EA-TDMA in W)
Pi	0.05 (Power demand in Idle Stage in W)
Te	0.1 × Td (Time to check buffer status in EA-TDMA)
p	0.6165 (Temperature) 0.01008 (Humidity) 0.37168 (X) 0.38608 (Y) 0.3764 (Z) 0.35 (Overall Probability)
W	10 (Window Size of data samples as used in Eq. 1)

The transmission probability of humidity sensor is very low due to very static data samples. Similarly, the transmission probability of accelerometer samples are moderate. The energy consumption results of S_2 and S_3 sensors are shown in Fig. 2 and Fig. 3. The percentage reductions in energy consumption achieved by DAABMA compared to EBMA range from approximately 41% to 73%, and compared to ABMA range from approximately 34% to 64% across the range of node counts analyzed in case of sensor S_2. The results indicate that the gap in energy consumption between DAABMA and ABMA/EBMA widens as the number of nodes increases. This is because DAABMA's energy savings grow with the increasing number of nodes, due to its lower transmission probability. As the node count rises, the number of redundant packets increases due to the low aggregated transmission probability, leading to greater overall energy efficiency.

The results show that the energy consumption of sensor S_2 is less (energy saving is more) as the transmission probability is less. However, transmission probability of S_3 is moderate thus energy saving is also moderate. In third case, the percentage reductions in energy consumption achieved by DAABMA compared to EBMA range from approximately 38% to 52% and with respect to ABMA 24% to 42% as shown in Fig. 3. The reason of energy saving for S_2 and S_3 is same as discussed for sensor S_1.

The overall energy consumption of all sensors are analyzed in Fig. 4. The analysis shows that the proposed DAABMA

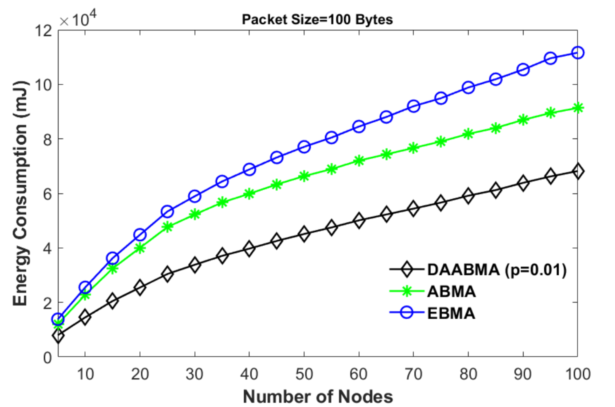

FIGURE 2. Energy consumption (in mW) vs number of nodes (S_2 humidity sensor).

protocol saves 40% to 54% energy with respect to EBMA and 28% to 44% with respect to ABMA. The energy savings achieved by DAABMA are particularly significant due to its low/moderate transmission probability, which strikes a balance between frequent data updates and energy conservation. By transmitting data only when deviations from previous readings (window of 10 previous samples) surpass dynamically adjusted thresholds, DAABMA minimizes unnecessary transmissions. This approach ensures that energy is conserved without compromising data accuracy. As the number of sensor nodes increases, the aggregated transmission probability decreases, resulting in fewer packet

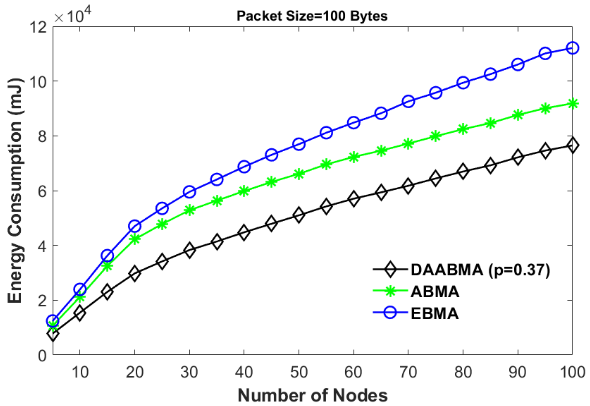

FIGURE 3. **Energy consumption (in mW) vs number of nodes (S_3 accelerometer sensor).**

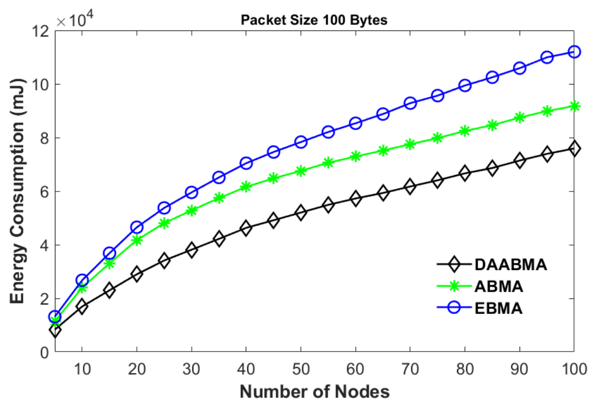

FIGURE 4. **Energy consumption (in mW) vs number of nodes (all sensors).**

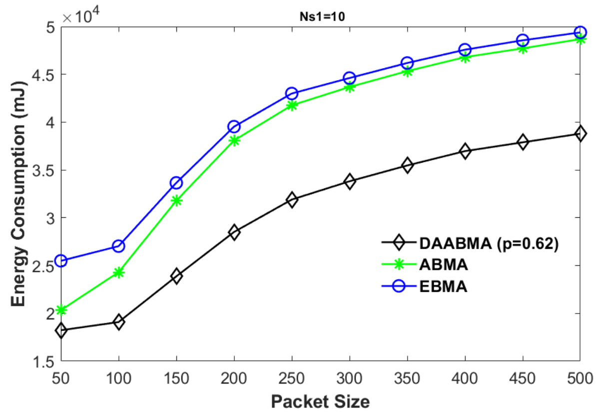

FIGURE 5. **Energy Consumption (in mW) vs Packet Size (Ns1 = 10).**

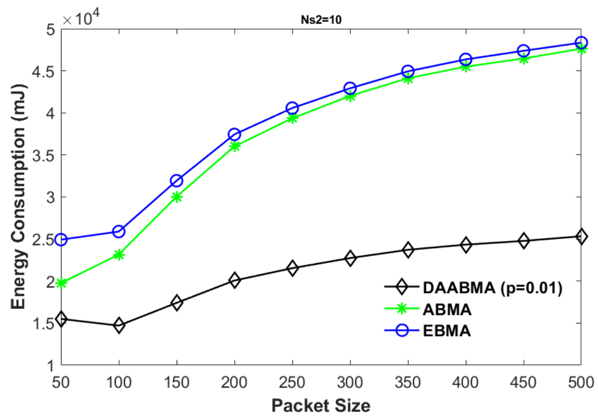

FIGURE 6. **Energy consumption (in mW) vs packet size (Ns2 = 10).**

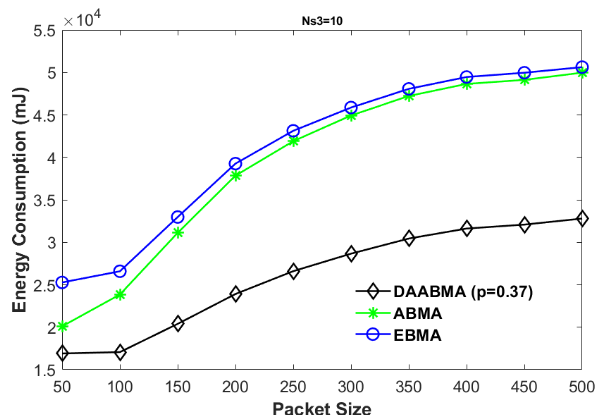

FIGURE 7. **Energy consumption (in mW) vs packet size (Ns3 = 10).**

transmissions and greater overall energy savings. Consequently, DAABMA effectively reduces energy consumption compared to ABMA and EBMA, demonstrating its efficiency in resource management for wireless sensor networks.

B. SCENARIO-2 (PACKET SIZE)

In this scenario, the packet size of SNs varies from 50 Bytes to 500 Bytes. The network performance is analyzed for individual sensors as well as overall sensors. In the first case, the temperature sensor ($N_{S1} = 10$) is analyzed as shown in Fig. 5. As the packet size increases, DAABMA consistently exhibits lower energy consumption compared to EBMA and ABMA. Overall, DAABMA achieves significant energy savings, with percentage reductions in energy consumption ranging from approximately 22% to 30% compared to EBMA, and approximately 20% to 28% compared to ABMA across the packet size analyzed as shown in Fig. 5. This proves the effectiveness of DAABMA in optimizing energy consumption in wireless sensor network.

Due to less transmission probability of sensor S_2, the energy saving of sensor S_2 is maximum and sensor S_3 it's moderate as shown in Fig. 6 and Fig. 7. Energy savings are lower for smaller packet sizes and higher for larger packet sizes. This is because, with smaller packet sizes, the overhead constitutes a larger proportion of the total packet, reducing efficiency. Conversely, with larger packet sizes, the overhead remains constant while the data portion increases, improving overall efficiency. Additionally, larger packet sizes make more efficient use of available bandwidth.

The overall energy consumption is analyzed for the 15 number of nodes as shown in Fig. 8. The result shows that the proposed method saves 44% energy with respect to ABMA and approx 52% energy with respect to EBMA.

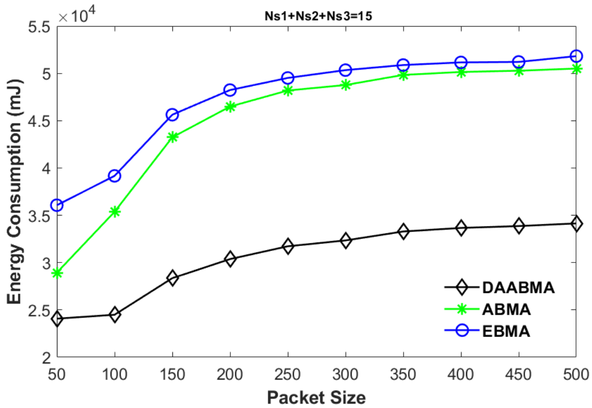

FIGURE 8. Energy consumption (in mW) vs packet size (Ns1 + Ns2 + Ns3 = 15).

Energy savings are more pronounced with larger packet sizes, especially at low transmission probabilities. With larger packets, the constant overhead becomes a smaller fraction of the total packet, increasing efficiency. At low transmission probabilities, fewer transmissions are needed, and with larger packet sizes, each transmission carries more data. This efficient use of bandwidth reduces the total number of transmissions required, leading to significant energy saving. Consequently, DAABMA demonstrates particularly high energy efficiency compared to ABMA and EBMA when the packet size is large and the transmission probability is low.

In both Scenario-1 (Number of Nodes) and Scenario-2 (Packet Size), DAABMA consistently outperforms EBMA and ABMA in terms of energy consumption across various configurations.These results underscore the effectiveness of DAABMA in optimizing energy consumption in wireless sensor networks, making it a promising approach for resource-constrained environments.

V. CONCLUSION

The proposed DAABMA protocol exhibits superior performance in terms of energy consumption compared to existing protocols EBMA and ABMA in wireless sensor networks. Through comprehensive analysis across varying scenarios of node counts and packet sizes, DAABMA consistently achieves significant energy savings ranging from approximately 11% to 42% compared to EBMA and approximately 20% to 28% compared to ABMA. These results highlight the effectiveness of DAABMA in optimizing energy usage, making it a promising solution for resource-constrained environments where energy efficiency is paramount. Further Research and real-world implementations could validate and enhance the practical applicability of DAABMA in diverse wireless sensor network deployments.

DECLARATIONS

ETHICAL APPROVAL

Ethics approval was not required for this study: Not Applicable

AVAILABILITY OF DATA AND MATERIALS

Machitje. The vibration sensor on railway lines. University of Pretoria. Dataset. https://doi.org/10.25403/UPresearchdata.24973911.v1

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