Facebook Prophet Library Prediction-Based Energy Harvested MAC Protocol (FPEH-MAC)

Vivek Kumar Verma[1], Satya Sai Srikant[2*]

[1,2]*Department of Electronics and Communication Engineering, SRM Institute of Science and Technology, Delhi-NCR Campus, Modinagar, Ghaziabad, Uttar Pradesh 201204 India. Email:* satya.srikant2311@gmail.com

[1]*Department of Electrical and Electronics Engineering, ABES Engineering College,Ghaziabad, Uttar Pradesh 201206 India.*

Abstracts: Data transfer within severe time constraints is crucial for wireless sensor networks used in mission-critical applications, such as industrial control and disaster monitoring. In such applications, exceeding time constraints and facing limitations in longevity can pose threats to human life. The primary option for powering wireless sensor networks is to utilize ambient energy sources like solar energy, thermal energy, etc., which are abundant in nature The lifetime and latency of these networks depend on a well-implemented duty cycle-based MAC protocol, and maximizing the duty cycle is achieved through efficient utilization of harvested and residual energy. Since harvested energy is inherently unpredictable, appropriate forecasting techniques are required. In this study, a prediction-based Energy Harvested MAC protocol (FPEH-MAC) based on the Facebook Prophet library is proposed to maximize the predicted duty cycle of the MAC protocol by forecasting harvested and residual energy. Additionally, this MAC protocol demonstrates an increase in residual energy and duty cycle, ensuring an extended lifecycle for the wireless sensor network. The suggested protocol was evaluated for latency, throughput, percentage increase in residual energy, and packet delivery ratio using OMNET, INET, Python, and MATLAB. The results of the analysis indicate that the proposed technique increases residual energy by 1.2%, enhances throughput by 33.33%, and reduces latency by 9.6% when compared to previous work.

Keywords: Wireless Sensor Network, Mission Critical Applications, Energy Harvesting, Prediction Techniques, MAC Protocol.

1. INTRODUCTION

Wireless Sensor Networks were originally designed for glacier and environmental monitoring applications where energy efficiency is a significant design priority. In this application case, such behaviour is not an issue because long end-to-end delays may be tolerated. For such situation, the nodes would have a lengthy lifespan because Exhaust battery replacement is a major issue in these difficult-to-reach areas. Wireless sensor node architecture consists of sensor, battery, transceiver, and microcontroller. Among all these components, Data transmissions via transceiver take the majority of the power, and when working within the network this power consumption takes place due to idle listening of channel, packet reception, transmission, overhearing, and even due to collision of data. Thus, in order to communicate effectively, MAC protocol is utilized, which optimizes energy efficiency by properly scheduling each sensor node's ON-OFF period, also known as the duty cycle. Reduced duty cycle [1-2] improves energy economy but increases end-to-end delay, which is not suitable in applications that are mission-critical [3-4].

Recently, Energy Harvesting was introduced in WSN, it can increase energy efficiency and boost performance by harvesting energy from the environment and utilizing it to maximize the duty cycle [5]. Medium Access Control (MAC) protocol takes care of both performance parameters by properly utilizing communication channels. Energy can be harvested from various sources of energy such as wind energy, solar energy, thermal energy, RF energy, etc. but among all these sources of energy, solar energy has the highest energy density and abundance [6].

1.1. Research Motivation

WSNs with energy harvesting capabilities can be employed in mission-critical applications [7] such as monitoring volcanic activity and delay-sensitive applications in industries where energy efficiency and enhanced data delivery

are necessary for the application to function effectively. The wireless sensor networks can also be employed in boiler temperature controlling and monitoring applications, in which the Sensors observe the temperature in the boiler and would deliver the messages to a supply interfaced with the heater element in a timely and reliable fashion. Another advantage of an Industrial Wireless Sensor Network is the reduction in cost and time required for the installation of huge cables, the flexibility of adding more sensor nodes, as well as the ease of maintenance of the entire system in difficult environments where cables may emerge in chemical or dangerous areas. As per Farag and his research team, the industrial applications were classified into three categories (a) safety, (b) control, and (c) monitoring applications [8]. Safety applications demand strict latency requirements in the range of 10 - 250 ms, whereas Control applications require latency requirements in the range of 10 – 500 ms, and lastly the Monitoring applications require latency requirements in the range from few seconds to days. The proposed method caters to the delay latency of Safety and control applications.

1.2. Major Contributions

This paper designs the Medium Access Control (MAC) protocol [9-11], which operates on the basis of Predicted Maximum Duty Cycle. This designed protocol is calculated on using the forecasted Harvested and Residual Energy. The purpose of this design protocol is not only to enhance the energy efficiency but also it reduces latency and increase throughput, all of which are essential conditions for mission-critical applications, such as safety and control applications in the industrial domain. Many researchers attempted several MAC protocols based on Energy Harvesting, all of which relied solely on the current harvesting condition but no one has attempted the MAC protocols with consideration of the analysis of past data trends and seasonality, which usually resulted in the inefficient use of harvested energy or potential energy shortages. Consequently, the full potential of available energy and optimization of crucial parameters could not be achieved. More recently, researchers began to focus on predicting harvested energy and optimizing the duty cycle, but these efforts were limited to individual sensor nodes rather than the entire network. Only a few related studies were reported that predicted harvested energy maximized the duty cycle, and then developed a MAC protocol based on these predictions. However, these studies suffered from research gaps, including poor prediction accuracy, high latency delays, and low throughput.

The major contributions of this research can be summarized as follows:

❖ The proposed method accurately forecasts harvested energy using the Facebook Prophet Library, complemented by a Hample filter to remove outliers.

❖ It achieves a high-value predicted duty cycle based on forecasted energy and residual energy.

❖ A high threshold value for residual energy is set, reducing the charge and discharge cycle length and improving battery lifespan.

❖ It effectively decreases end-to-end delay latency while enhancing throughput.

❖ The performance is compared with the latest state-of-the-art protocols, including SS-MAC, AD-MAC, and PADC-MAC.

❖ Observational results demonstrate that FP-EHMAC outperforms SS-MAC, AD-MAC, and PADC-MAC in terms of prediction accuracy, delay latency, and throughput.

2. METHOD

2.1. Proposed Architecture

The primary objective of this research is to design a MAC (Medium Access Control) protocol with a maximum predictive duty cycle based on forecasted harvested energy and residual energy. This protocol aimed to ensure optimized delay, an extended lifespan, and high throughput. The proposed network configuration, as depicted in

Fig1, adopts a star network architecture, where sensors communicate wirelessly with a central gateway. Data collected by the gateway from the sensors is then transmitted to the server via an Ethernet connection, facilitating connectivity with other networks. In this research, it was assumed that the gateway possessed greater processing capacity and a stable power supply, while the sensors were equipped with limited resources and relied on harvested energy and residual energy, aligning with the concept of harvesting and storing energy.

2.2. Proposed Methodology

It is observed that in the initial phase, Gateway forecasted solar Energy for the future slots and transmitted it to sensors. The sensor nodes used in this Forecast and Residual Energy of the battery are to calculate the Predicted Duty cycle for future slots and tried to maximize it. After this, the predicted Duty cycle is transmitted back and Gateway are used these values to calculate the average duty cycle for each slot and send these values back to each sensor. Now each sensor and Gateway work on average predicted energy, which will reduce the burden on Sensors that have limited sources as compared to the Gateway.
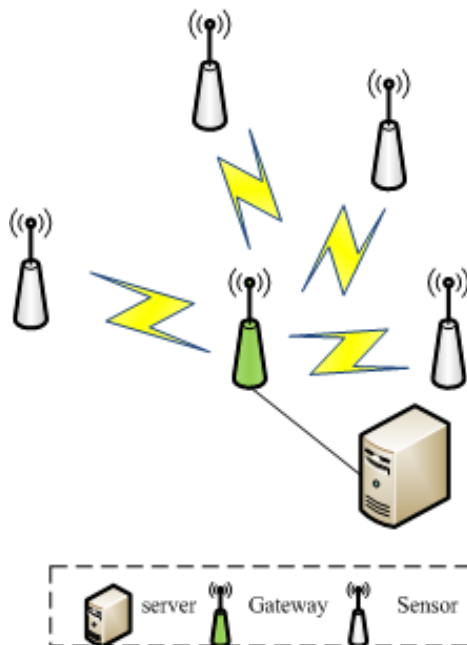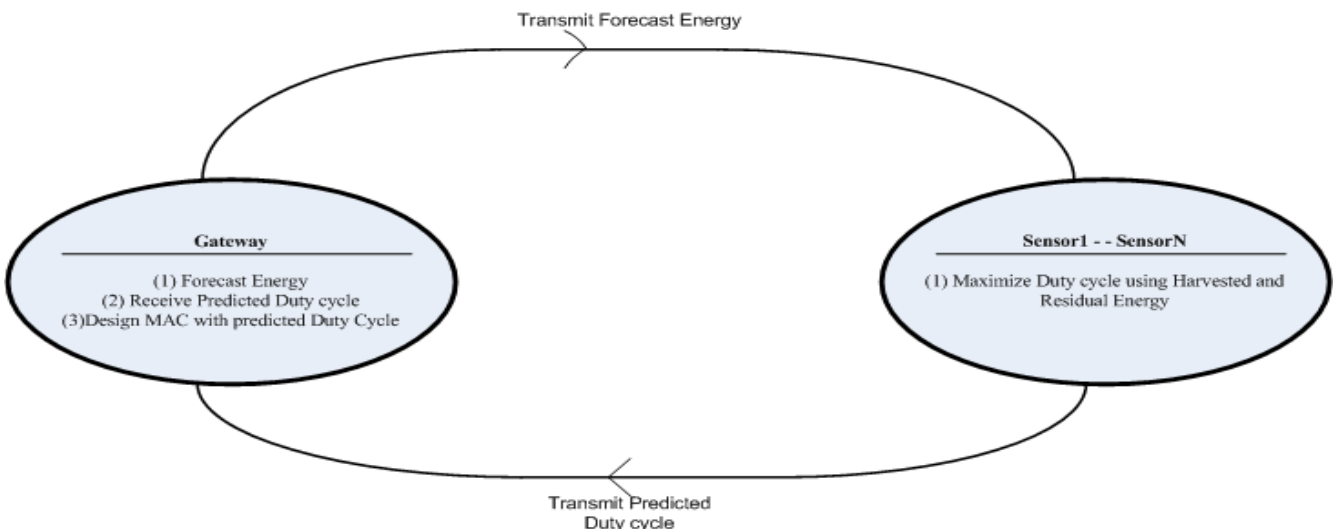

Fig 1: Proposed Network Architecture

Fig 2: Proposed Methodology for PEH-XMAC

The proposed work was completed to reach the desired result with a number of steps (as shown in Fig 2), each of which are described below.

2.3. Solar Energy Prediction

As solar energy is known for its unpredictable nature, along with temporal and spatial variations, it was crucial to adopt a suitable prediction methodology capable of accommodating data trends and seasonality. In our current research, we employed the Hample filter to remove outliers before harnessing the power of the Facebook Prophet library for forecasting harvested energy. This approach is based on a method developed in our previous work [12].

The Facebook Prophet library, designed as an open-source tool for univariate forecasting, provides highly accurate predictions by taking into account seasonality, holiday effects, and non-linear patterns. Our research outcomes demonstrated that using training data spanning from June 2010 to 2015 for forecasting in June 2016 produced superior results compared to employing previous machine learning techniques on the same dataset. Fig 3 provides a visual representation of the forecasted harvested energy for June 18, 2016.
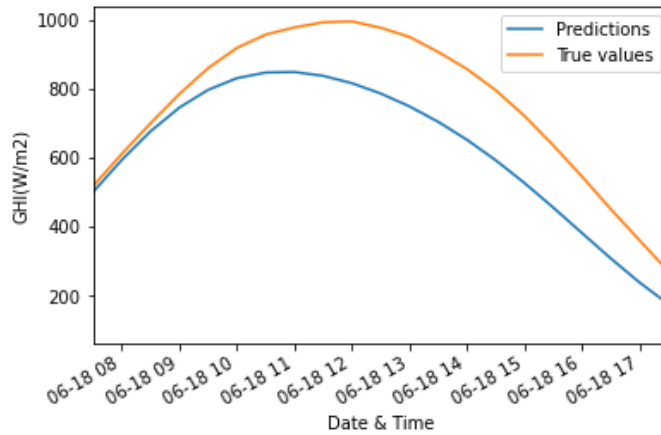
.

Fig 3: Forecasted Harvested Energy for 18/06/23 using Facebook prophet library.

2.4. Duty cycle maximization using Harvested and Battery Residual Energy

According to Kansal et al.[13], predicted energy and energy consumed by the sensor node are continuous, and their average values are bounded by parameters α_1, α_2 and α_3, α_4 respectively.

$$\int_{t1}^{t1+T} P(t)_{\text{Pr}edicted} dt = \rho_1 T + \alpha_1 \tag{1}$$

$$\int_{t1}^{t1+T} P(t)_{\text{Pr}edicted} dt = \rho_1 T - \alpha_2 \tag{2}$$

$$\int_{t1}^{t1+T} P(t)_{Consumed} dt = \rho_2 T + \alpha_3 \tag{3}$$

$$\int_{t1}^{t1+T} P(t)_{Consumed} dt = \rho_2 T - \alpha_4 \tag{4}$$

ρ_1, ρ_2 Denotes the average harvesting and power consumption rates, respectively, whereas and implies the

highest and least bustiness in harvested and used energy, respectively. In our suggested study, we assumed constant power consumption ($\alpha_3 = 0, \alpha_4 = 0$) and estimated the value of $\rho_1, \alpha_1, \alpha_2$ for the month of June for the year 2010 to 2015 which came out to be 105mw, $4.630 \times 10^3\, J$ and $3.697 \times 10^3\, J$ respectively. In adherence to the Electrically Neutral Condition (ENO), it is imperative that the total harvested power consistently surpasses the consumption power. Consequently, to determine the minimum battery capacity needed to sustain the entire system, we consider the worst-case scenario, which comprises (1) the minimum harvested energy and (2) the maximum power consumption.

$$B_{Capacity} + \eta * \min \int_T P_{Harvested}\, dt - \max \int_T P_{Consumed}\, dt - \int_T P_{leak}\, dt \geq 0 \tag{5}$$

$$B_{Capacity} + \eta * (\rho_1 T - \alpha_2) - (\rho_2 T + \alpha_3) - P_{leak} T \geq 0 \tag{6}$$

Equating $T \to 0$ in Eq.6 Gives the Required battery capacity

$$B_{Capacity} \geq \eta * \alpha_2 + \alpha_3 \tag{7}$$

We assume $\alpha_3 = 0$ that Eq. (7) yields the maximum capacity of the Battery B_{max}

$$B_{max} = \eta * \alpha_2 \tag{8}$$

For $T \to \infty$ in Eq (6) gives the Condition for maximum Power consumption

$$\rho_2 \leq \eta * \rho_1 - \rho_{leak} \tag{9}$$

$$\rho_{2\max} = \eta * \rho_1 - \rho_{leak} \tag{10}$$

Here ρ_2 is average power consumption and it is related to the Duty cycle by the following Relation

$$\rho_2 = D(i) \times P_{Active} + (1 - D(i)) \times P_{Sleep} \tag{11}$$

So from Eq.11, it has been observed that on increasing the duty cycle, the Power consumption will increase and it will compensate on using Harvested Energy. On equating Eq. (9) and Eq. (11), one can achieve a maximum duty cycle of 73% on substituting the variable values as mentioned in Eq.(12). The observations still show the compliance with the Electrically Neutral Condition (ENO). However, mission-critical applications necessitate a duty cycle as high as 90%.

$$\eta * \rho_1 - \rho_{leak} \geq D(i) * P_{Active} + (1 - D(i)) * P_{Sleep}$$

$$D(i) \leq (\eta * \rho_1 - \rho_{leak} - P_{Sleep}) / (P_{Active} - P_{Sleep})$$

$$D(i)_{Eno\max} = (\eta * \rho_1 - \rho_{leak} - P_{Sleep}) / (P_{Active} - P_{Sleep}) \tag{12}$$

To meet this requirement, the harvested energy and residual battery energy has been employed to further boost the duty cycle. In this scenario, the initial prediction algorithm to calculate the harvested energy for K time slots has been evaluated and then subsequently summed these values according to Eq.13.

$$E_{Sum} = \sum_{i=1}^{K} P(i)_{\Pr edicted} \tag{13}$$

After that, the algorithm starts assigning $D = D_{\max}$, where $D_{\max}$ desired Duty cycle till enough Energy was left. In the second phase of the algorithm, Residual Battery energy was used to further the boost Duty cycle of leftover slots.

2.5. MAC Protocol Design based on Predicted Average Duty Cycle

In this stage, the Gateway optimizes the MAC protocol by calculating the average of the Predicted Duty cycle received from each sensor node. In mission-critical applications, the data sent by the sensor node is random in nature and in this case, MAC will be asynchronous in nature. This asynchronous protocol can be either receiver-initiated or sender-initiated [14]. In an industrial network, it has been assumed that the receiver (Gateway) was not resource-constrained therefore, this paper utilizes a sender-initiated asynchronous protocol. In this case, whenever the sender has data to transmit, it initiates the process by sending a strobed preamble. The preamble's duration is at least equal to the sleep interval of the receiver and also carries the receiver's address. When the receiver wakes up and detects the preamble, it sends an acknowledgment.

The base protocol employed in this scenario is the XMAC protocol [15], with several modifications, including (1) aperiodic data transfer, (2) energy harvesting features, (3) energy management features, and (4) a high data rate. With each sensor node operating on a specific duty cycle, the likelihood of data collisions is significantly reduced.

The total Energy consumed by the sensor node is given as

$$E_{Total} = E_{\mathrm{Re}\,c} + E_{Trans} + E_{Listening} + E_{Sleep} + E_{Sampling} \tag{14}$$

Where $E_{\mathrm{Re}\,c}$, E_{Sleep} and was Energy consumed in Receiving, transmitting, Listening, sleeping, and Sampling the data. To design the protocol for mission-critical applications, the Sampling of data was selected randomly in nature in the interval between 0 to 1 second so the rate of sampling of data is given as

$$r = \frac{1}{random(0s,1s)} \tag{15}$$

Energy consumed in a sampling of data was calculated as

$$E_{Sampling} = t_{Dtata} \times \frac{1}{random(0s,1s)} \times I_{Sample} \times V_{Supply} \tag{16}$$

Where I_{Sample} represents current consumed during sampling and V_{Supply} shows the power supply.

The Energy consumed in the transmitting packet is shown in eq (17)

$$E_{Trans} = T_{Transmitting} \times I_{Transmitting} \times V_{Supply} \tag{17}$$

Where $T_{Transmitting}$ represents the total time to transmit Strobed preamble Data Packet and $I_{Transmitting}$ provides the current consumed during transmitting and former is expressed as

$$T_{Transmitting} = \frac{1}{random(0s,1s)} \times (L_P + L_P) \times T_{T\_1byte} \tag{18}$$

The end-to-end delay for single-hop transmission was calculated as

$$L_{hop} = (preambIe\ Time + Acknowledge\ Time) \times (probable\ iterations) + (Time\ to\ send\ one\ packet)$$

$$= \left(\frac{1}{\left(\frac{R_{Listen} - R_{Sleep}}{R_{Listen} + R_{Sleep}} \right)} \right) * (P_t + Ack_t) + D_t \tag{19}$$

The above equations provide that there is an increment in the listening time or duty cycle, which leads to a decrease in the end-to-end delay for single-hop data transmission. Therefore, the objective of this paper is to increase the average duty cycle using predicted harvested energy and residual energy and transmit this information to each sensor node. The operation of the proposed FPEH-XMAC is depicted in Fig 3, and the finite state machine model is shown in Fig 4.

In the proposed work, during the initialization phase, the Gateway first forecasts harvested energy for future slots and multicasts these values to each sensor node. Upon receiving these forecasted harvested energy and available residual energy values, each sensor node calculates the duty cycle for future slots. While other sensor nodes are in a sleep state during this period, the active sensor nodes sense the channel and transmit these values back to the gateway. This way, the gateway collects these values from each sensor node.

The Gateway calculates the average duty cycle for each slot and returns this result to each sensor node on using the corresponding collected anticipated duty cycle for the same slot,. With all sensor nodes operating on the same duty cycle, the general structure of the MAC protocol becomes simpler. After the startup procedure is complete, all sensor nodes go to sleep and wake up to check their residual energy levels. If their energy levels are above the threshold, they randomly detect a free channel and transmit a strobed preamble to the gateway. All sensors, except the gateway, go back to sleep after transmitting the preamble since the destination address is contained within it. This approach prevents energy waste due to idle listening. The gateway transmits an acknowledgment upon receiving the strobed preamble, and the sensor sends data to the gateway after receiving the acknowledgment.
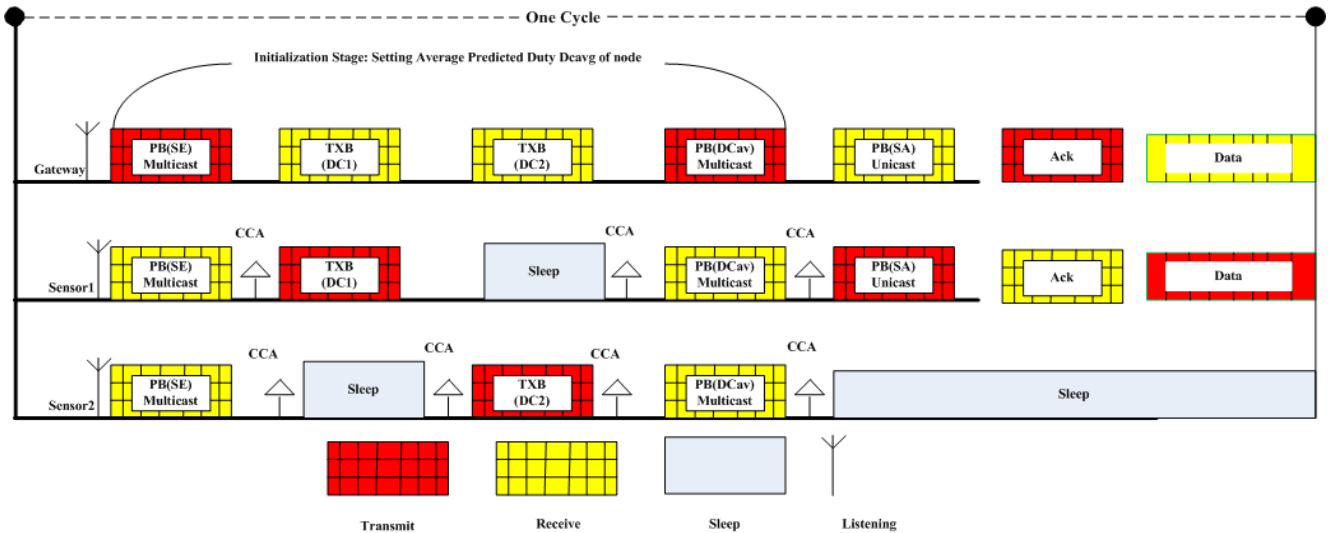

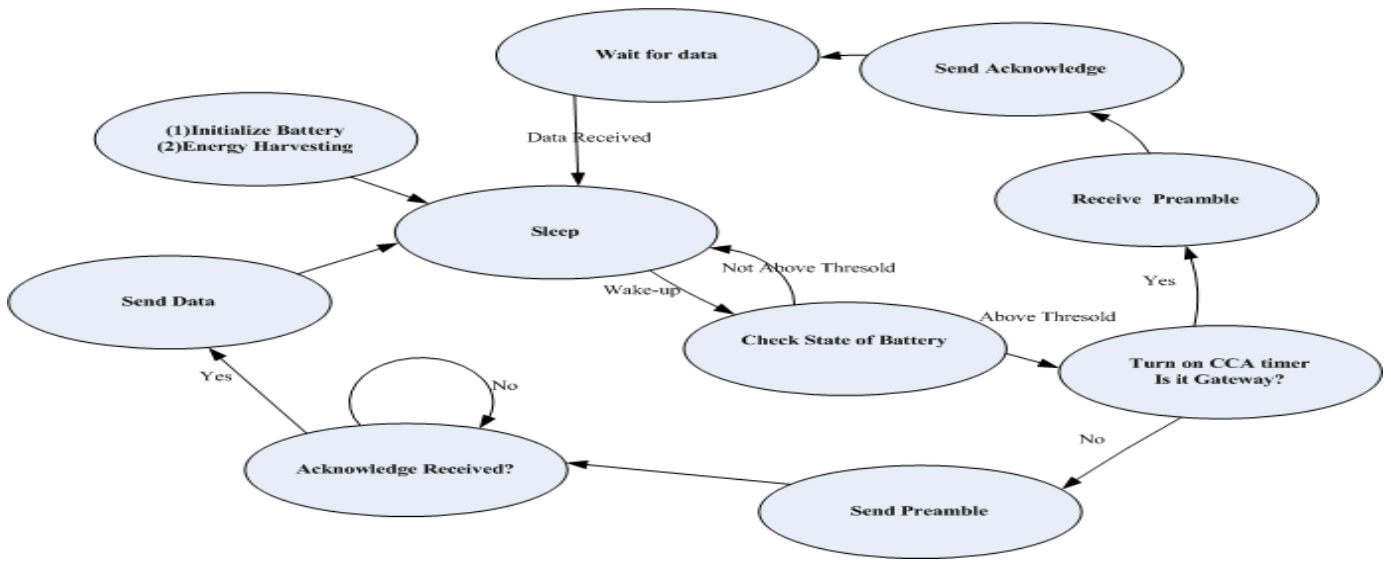**Fig 4**: Working of proposed PEH-XMAC protocol

Fig 5: Finite state model

3. RESULTS AND DISCUSSIONS

In mission-critical applications, latency leads to the failure of the system and even leads to potential threats to human life. In the proposed work lifetime and latency problems were catered by using Energy Harvesting and Increased Duty cycle. Solar energy is estimated for future slots to boost the anticipated duty cycle. To anticipate 24 hours ahead in June for the year 2016, the NREL dataset for June from the years 2010 to 2015 was used. Data was cleaned using the MATLAB-implemented Hample filter before applying the model, and after that, Facebook Prophet Library was used to forecast outcomes.In the second part, Algorithms predicted an Average duty cycle of more than 90% using Harvested energy and Residual Energy, The final part, FPEH-XMAC was implemented using OMNET simulator as shown in Fig.4 with Five sensor nodes, gateway, and server, in this network sensor connected to a gateway through wireless links whereas gateway connected to the server through dedicated Ethernet link. Simulation runs with various values of duty cycle along with predicted duty cycle and evaluates the following parameters (1) End-to-end delay (2) Throughput (3) Residual Energy. In the proposed work slot duration or sleep duration of Gateway and sensor nodes given by Eq.20

Slot duration or sleep duration of sensor node = 2.5 x Slot duration of Gateway   (20)
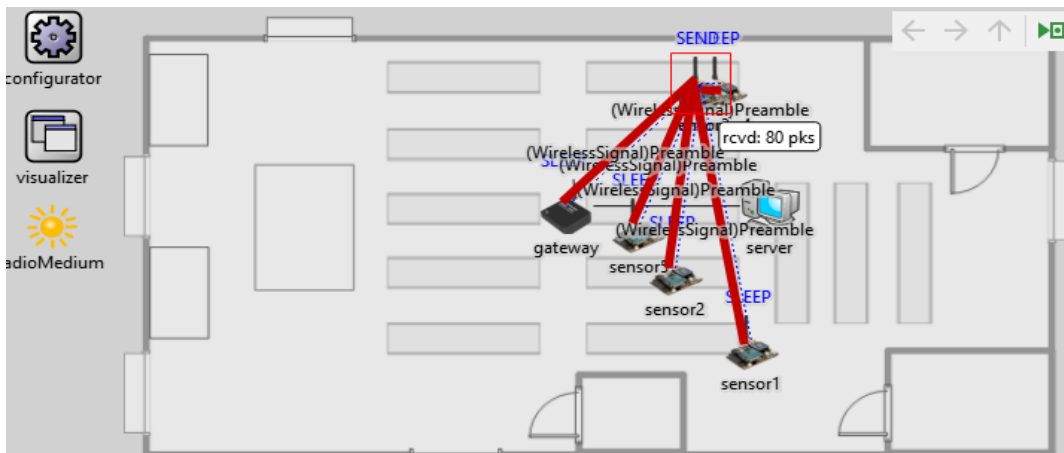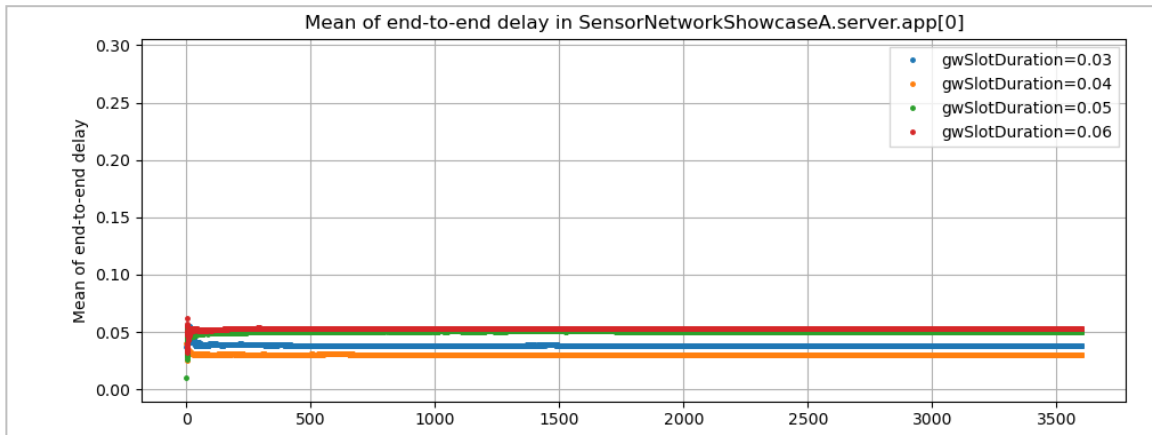

Fig 6: PEH-XMAC network

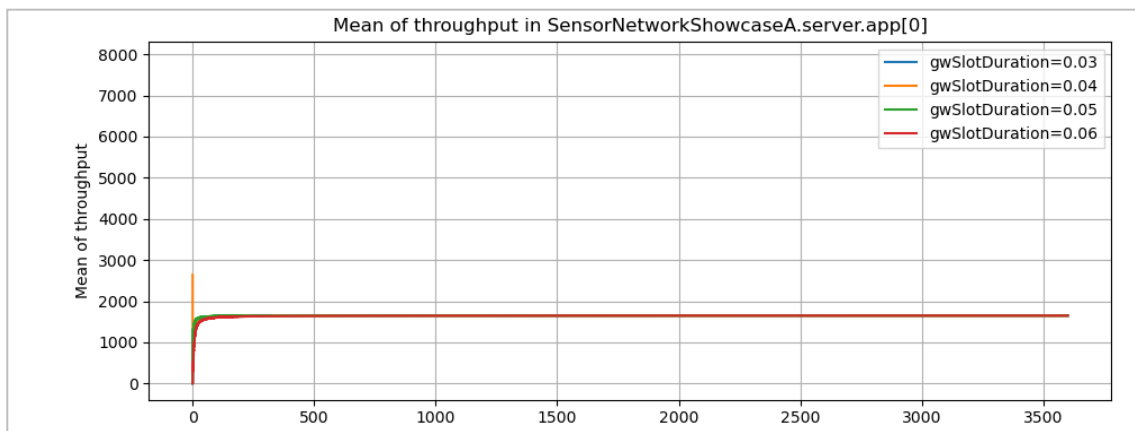**Fig 7** End to end delay of sensor nodes for various slot duration

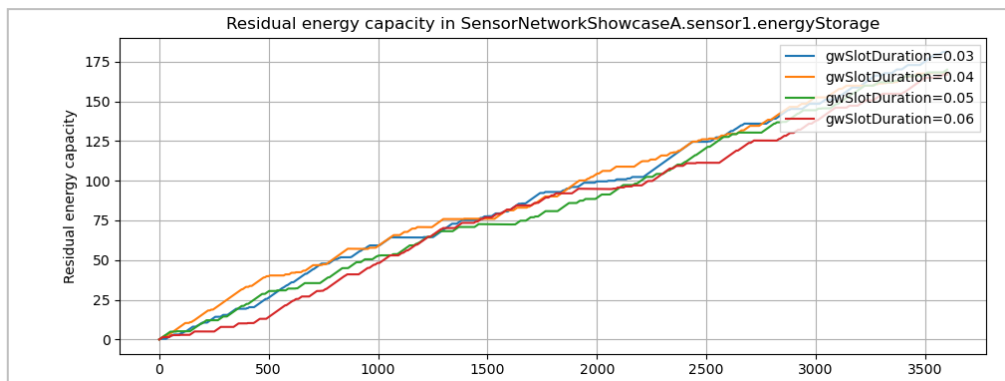**Fig 8** Throughput comparison for various slot duration

Fig 9. Residual Energy of Battery for various slot duration

In this paper, the threshold energy of the residual battery level was set to 60% of the total available energy. It means that whenever the residual energy falls below the threshold level, it will stop transmitting and resume transmission until it reaches the threshold level again. According to Fig 9, due to harvested energy and the proper design of the MAC protocol, the residual energy never depletes and also it adds 176 Joules of energy to the battery in 1 hour of simulation, or in other word, the total energy is increased by 1.36%. Fig 7 and Fig 8 represent the corresponding End-to-End delay and Throughput of the simulated network.

Table 1 shows the comparison of FPEH-XMAC with various mission-critical MAC protocols, and according to this table, it was concluded that harvesting can improve the performance parameters compared to non-harvesting

87

scenarios. The FPEH-XMAC MAC protocol, with a predicted duty cycle of 90%, yields an End-to-End delay, throughput, percentage increase in residual energy, and packet delivery ratio (PDR) of 28 ms, 1600 bps, 1.2%, and 100%, respectively. These results demonstrate an improvement compared to previous work.

TABLE 1 Comparison of Performance parameters with the recent work

MAC protocol	Year	Duty cycle (%)	End-to-end delay (ms)	Throughput (bps)	Residual Energy (%)	Packet Delivery Ratio (PDR)	Energy Harvesting	Lifetime
Wir Arb [17]	2015	NA	45.248ms	510bps	NA	100%	NO	Limited
SS-MAC [8]	2018	NO	40	NA	NA	NA	NO	Limited
AD-MAC [17]	2019	20 to 40	100	280	NA	100%	NO	Limited
PADC [18]	2023	45 to 100	31ms	1200	+1%	100%	Yes	Infinite
FPEH-XMAC Proposed Design	2023	90%	28ms	1600	+1.2%	100%	Yes	Infinite

CONCLUSIONS

Energy Harvesting is a future of mission critical applications to power Wireless sensor network to enhance lifetime along with low End-to end delay. However, ambient energy such as solar energy which is stochastic in nature, shows variation with respect to time and place. So, it requires suitable prediction Technique to forecast energy and hence it is very much necessary to design MAC protocol based on maximum predicted Duty cycle. This predicted Duty cycle was maximized using forecasted Harvested energy as well as Residual energy, which helps in decreased the latency, increased the Throughput and increased the Residual energy. In this paper, FPEH-XMAC MAC protocol is designed which incorporates the forecast harvested Energy, predicted Duty cycle and MAC protocol. For forecasting, Facebook prophet library was used and data was cleaned from outlier using Hample filter.

The FPEH-XMAX performances were evaluated in terms of End-to end delay, Throughput, Residual energy and Packet delivery ratio. The simulation was carried out for 1 hour of duration using OMNET INET. The simulation results of proposed protocol (FPEH-XMAC) was compared with previous protocols and it shows excellent performance with reduction by 39.3%,72%,9.6% with respect to existing protocols SS-MAC, AD-MAC and PADC respectively. The result also increases the Throughput by 33.33% as compared to PADC-MAC. Future studies are in process for multi hop network.

ACKNOWLEDGEMENTS

REFERENCES

[1] Habeeb I J, Jasim H A, Hashim MH. Balance energy based on duty cycle method for extending wireless sensor network lifetime. Bulletin of Electrical Engineering and Informatics. 2023;12(5):3105–14.

[2] Ye D, Zhang M. A self-adaptive sleep/wake-up scheduling approach for wireless sensor networks. IEEE Transactions on Cybernetics. 2017; 48(3):979–92.

[3] Suriyachai P, Roedig U, Scott A. A survey of MAC protocols for mission-critical applications in wireless sensor networks. IEEE Communications Surveys & Tutorials. 2011;14(2):240–64.

[4] Raut AR, Khandait SP, Dongre SS. A machine learning based mission critical data transmission protocol in wireless sensor networks. In: 2021 6th international conference on communication and electronics systems (ICCES) IEEE; 2021:846–52.

[5] Kansal A, Hsu J, Srivastava M, Raghunathan V. Harvesting aware power management for sensor networks. Proc - Des Autom Conf. 2006;651–6.

[6] Sah DK, Amgoth T. Renewable energy harvesting schemes in wireless sensor networks: A survey. Information Fusion. 2020; 63:223–47.

[7] Deif D, Gadallah Y. A comprehensive wireless sensor network reliability metric for critical Internet of Things applications. EURASIP Jr on Wireless Communications and Networking. 2017; 145:1–18.

[8] Farag H, Gidlund M, Österberg P. A delay-bounded MAC protocol for mission-and time-critical applications in industrial wireless sensor networks. IEEE Sensors Journal. 2018; 18(6): 2607–16.

[9] Sherazi HHR, Grieco LA, Boggia G. A comprehensive review on energy harvesting MAC protocols in WSNs: Challenges and tradeoffs. 2018; 71:117-134.

[10] Deb M, Roy S. Enhanced-pro: A new enhanced solar energy harvested prediction model for wireless sensor networks. Wirel Pers Commun. 2021; 117:1103–21.

[11] Liu F, Jiang C, Xiao W. Multistep prediction-based adaptive dynamic programming sensor scheduling approach for collaborative target tracking in energy harvesting wireless sensor networks. IEEE Trans Autom Sci Eng. 2020; 18(2):693–704.

[12] Verma VK, Srikant SS. Hample filter based Short term Solar Forecasting using Facebook Prophet Library in Energy Harvested Wireless Sensor Network (EHWSN). IEIE Trans Smart Process Comput. 2022; 11(5):368–75.

[13] Kansal A, Hsu J, Zahedi S, Srivastava MB. Power management in energy harvesting sensor networks. ACM Trans Embed Comput Syst. 2007; 6(4):32-es.

[14] Verma VK, Kumar V. Review of MAC Protocols for Energy Harvesting Wireless Sensor Network (EH-WSN). Internet Things Big Data Appl Recent Adv Challenges. 2020; 141–9.

[15] Buettner M, Yee G V, Anderson E, Han R. X-MAC: a short preamble MAC protocol for duty-cycled wireless sensor networks. In: Proceedings of the 4th international conference on Embedded networked sensor systems. 2006; 307–20.

[16] Zheng T, Gidlund M, Åkerberg J. WirArb: A New MAC Protocol for Time Critical Industrial Wireless Sensor Network Applications. IEEE Sens J. 2016; 16(7):2127–39.

[17] Sakya G, Sharma V. ADMC-MAC: Energy efficient adaptive MAC protocol for mission critical applications in WSN. Sustain Comput Informatics System. 2019; 23:21–8.

[18] Sarang S, Stojanović GM, Drieberg M, Stankovski S, Bingi K, Jeoti V. Machine Learning Prediction Based Adaptive Duty Cycle MAC Protocol for Solar Energy Harvesting Wireless Sensor Networks. IEEE Access. 2023;11:17536–54.