

A MAC-Protocol for Passive Wake-up Radios

Hilal Bello^{1,*}, Ibrahim Nasidi²

¹Department of Information and Communication Engineering, Usmanu Danfodiyo University, Sokoto, Nigeria, hilal.bello@udusok.edu.ng

²Department of Electrical and Electronics Engineering, Usmanu Danfodiyo University, Sokoto, Nigeria, ibronasidi@yahoo.com

*Corresponding author's Email: hilal.bello@udusok.edu.ng

ABSTRACT

Energy efficiency remains a big challenge in wireless sensor networks and the internet of things (IoT) since sensor nodes have limited energy resources. Conventional duty-cycled medium access control (MAC) protocols reduce idle listening while incurring energy cost owing to periodic channel monitoring. Wake-up radio technology has emerged as a potential solution for on-demand node activation and reducing idle listening. In this paper, a passive wake-up radio MAC protocol is proposed for energy-constrained IoT sensor networks. Sensor nodes are awakened via radio frequency (RF) energy harvesting from received wake-up signals. To analyze packet transmissions and node energy consumption, a cross-layer analytical framework is created that incorporates physical layer wake-up processes and MAC layer communication behavior. Closed-form expressions are constructed for critical packet statistics such as wake-up calls, acknowledgements, and erroneous wake-up events, allowing for extensive study of protocol performance. The proposed protocol is evaluated using discrete-event simulation with different wake-up call durations and packet loss probabilities. Simulation results show that the proposed passive wake-up protocol consumes much less node energy than traditional duty-cycled and existing wake-up radio MAC methods while retaining acceptable communication delay and reliability. Simulation results show that, in comparison to conventional duty-cycled and benchmark wake-up radio MAC protocols, the proposed passive wake-up protocol reduces average node energy usage by more than 50% while maintaining acceptable packet reliability and delay. The operating lifetime of large-scale IoT deployments could be greatly extended by passive wake-up radio systems, according to these quantitative results.

Keywords: Wake-up radio, Energy harvesting, IoT, Wireless sensor networks, MAC protocol, Energy efficiency

1 INTRODUCTION

Duty cycling, also referred to as "sleep scheduling," has long been a key method for extending the lifespan of wireless sensor networks (WSNs) by lowering energy consumption brought on by sensor nodes' idle listening and overhearing (Adam *et al.*, 2019). This method saves energy by having the radio switch between active and sleep modes according to predetermined timings. Duty cycle is efficient, but it comes with a number of drawbacks, such as synchronization costs, higher latency, and the possibility of missing packet receipt while you're sleeping (Kim & Cho, 2022; Liu *et al.*, 2021).

Traditional duty-cycling systems are becoming less and less suitable for ultra-low-power applications due to the fast expansion of IoT, which is characterized by huge device connection and strict energy limits (Akyildiz *et al.*, 2022; Djouaniet *et al.*, 2020; Nguyen *et al.*, 2023). Communication protocols that minimize energy usage while preserving dependability and low latency are especially necessary for IoT deployments in smart agriculture, environmental monitoring, and industrial automation ((Djenouriet *et al.*, 2025); Zhang *et al.*, 2024).

Wake-up radio (WuR) technology has become a viable substitute to overcome these constraints. Wake-up radio systems eliminate idle listening and wasteful energy use by having an auxiliary low-power receiver continually listen for a wake-up signal and only activate the main transceiver when needed (Basagniet *et al.*, 2022; Ben Arbiaet *et al.*, 2021; Famitafreshiet *et al.*, 2022; Piyareet *et al.*, 2021). When compared to duty-cycled systems, this method greatly increases network longevity and scalability.

Recent developments have further investigated passive wake-up radio systems, which use ambient or incoming RF

signals to power the wake-up receiver using energy harvesting techniques. This allows for nearly minimal standby energy usage and removes the requirement for a constant power supply to the wake-up receiver (Ben Arbiaet *et al.*, 2021; Clerckx *et al.*, 2022; Magnoet *et al.*, 2021). Thus, RF energy harvesting has emerged as a crucial facilitator for sustained IoT connectivity, especially in distant and battery-constrained installations (Lu *et al.*, 2023).

However, compared to active wake-up systems, passive wake-up radios present additional difficulties, such as a shorter communication range, higher wake-up latency because of energy buildup, and lower receiver sensitivity (Sanchez-Iborraet *et al.*, 2021). Longer wake-up signal transmission lengths also put additional energy demands on transmitting nodes, which reduces network efficiency (Simeone *et al.*, 2022).

The success of wake-up radio systems is largely dependent on the medium access control (MAC) architecture at the protocol level (Guo *et al.*, 2024). Energy consumption and network dependability can be greatly impacted by issues including collision avoidance, retransmission techniques, and false wake-up events, which must be addressed by efficient MAC protocols (Djouaniet *et al.*, 2020; Kocaet *et al.*, 2023; Yadav *et al.*, 2021). In order to improve system performance, recent research has focused on cross-layer optimization techniques that combine physical layer properties with MAC layer design (Rahman *et al.*, 2024). In this work, a passive wake-up radio MAC protocol is presented using a cross-layer design approach that integrates both physical (PHY) and medium access control (MAC) considerations. The proposed model aims to minimize energy consumption while maintaining acceptable latency and reliability. The system architecture,

Radio states with solid lines are stable, meaning the radio can remain in these states for a long period of time. Transition states are indicated by dotted lines, and the

amount of time spent in these states is indicated inside brackets. In addition, the power consumption for each state is displayed outside the states.

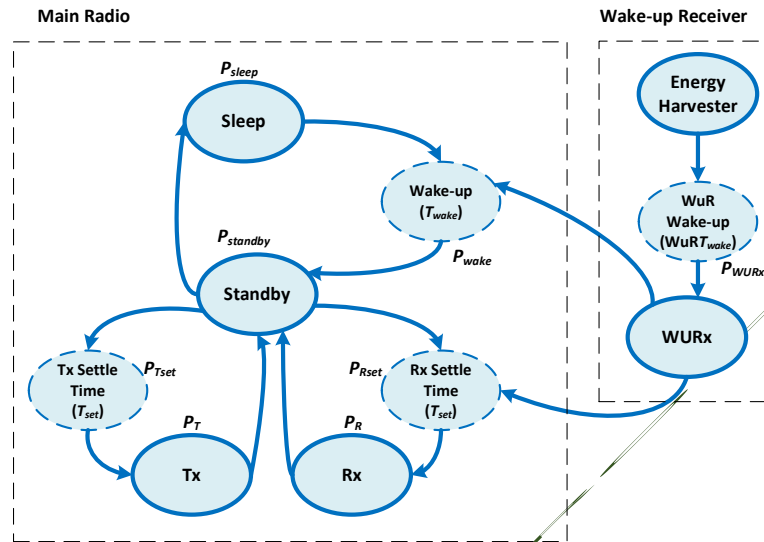


Figure 2. Radio state transition diagram

Sleep mode uses the least amount of power, whereas standby mode consumes more power. Conversely, the radio can wake up more quickly when it is in standby mode than when it is in sleep mode. In this regard, staying in the sleep mode as opposed to the standby mode can be disadvantageous given the amount of energy required to wake up from the sleep mode.

In some radios, sleep and standby modes are not provided or settling time is not required between receiving and transmitting. For the former case, T_{wake} should be set to zero, and for the latter, T_{set} should be zero. Both parameters must be set to 0 when the radio is always on and does not need to settle.

3 Proposed Passive wake-up MAC Protocol

In this section, the proposed MAC protocol for passive wake-up is presented along with the description of its working principles. First described is the wake-up communication procedure, which includes collision mitigation, acknowledgement processing, and wake-up call delivery. A thorough examination of the wake-up cycle timing, which establishes the prerequisites for effective node activation and communication, comes next.

3.1 Wake-Up Procedure

Considering a network consisting of a master node and nodes attached to passive wake-up receivers, the master node sends wake-up calls (WUC) and awaits the passive wake-up receiver on the node to harvest energy, wake up the node and transmit an acknowledgment (ACK). The network considers the clear channel assessment (CCA) method to mitigate collision. It is necessary to retransmit a WUC or ACK packet when a packet fails with probability

p_{fail} . As a result, the wake-up process can only be performed after $N_{WUC(MAX)}$ transmissions have been made; the transmitter shuts down and the wake-up process fails after this number of transmissions. A counter value representing the remaining transmissions is transmitted by each WUC. The receiver can determine the precise number of times it can transmit an acknowledgment thanks to this counter value. Until a connection is established or the allotted number of transmissions is reached, nodes will continue to send acknowledgments.

A fake wake-up occurs when a node receives a WUC that was meant for another node. Once this occurs, the node sends fake acknowledgement (FACK) packets. Fake wake-up event causes overhearing, which results in higher energy usage. The probability p_{fake} indicates the likelihood of a fake wake up.

3.2 Wake-Up Cycle Timing

Figure 3 illustrates a detailed wake-up cycle. The same radio state model depicted in Figure 2 are used as the radio parameters. Only when the nodes enter deep sleep do the wake-up periods manifest. The listen period, T_{listen} is given as

In order for the wake-up radio to harvest enough RF

$$T_{listen} = T_{EH} + T_{ACT} \quad (1)$$

energy and for WURX to wake up the node when the wake-up cycle begins, two WUCs need to take place and fit in within the listen period, T_{listen}

$$T_{listen} > 2(T_{set} + T_{wuc}) + T_{pkt} + T_{wake} \quad (2)$$

Additionally, the listen time cannot be longer than the time for the complete cycle $T_{listen} \leq T_{cycle}$.

$$T_{listen} \leq T_{cycle} \tag{3}$$

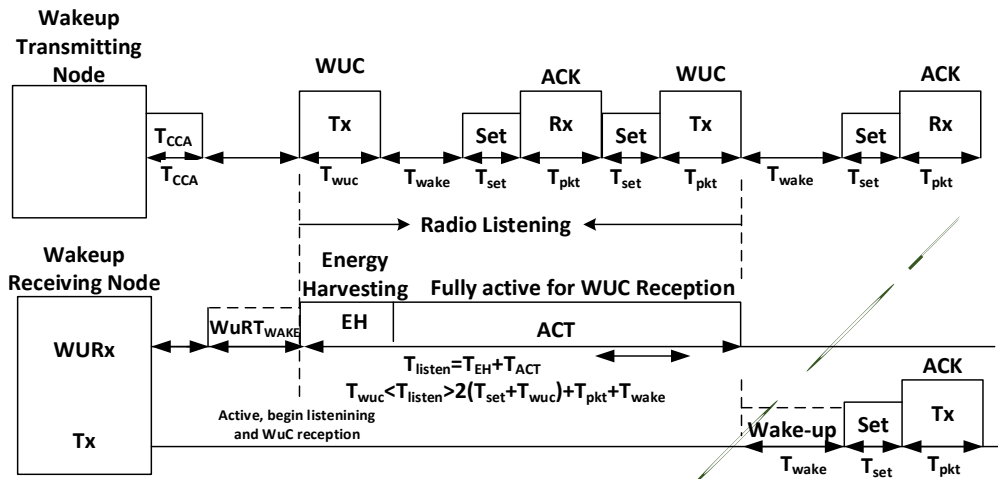


Figure 3. Detailed view of a wakeup event

Both the *WUC* and *ACK* packets have the same length k . The main radio bit rate R_b and the WUR_x bit rate R_{bw} may differ, according to which the *WUC* and *ACK* packet durations may vary,

$$T_{wuc} = \frac{k}{R_{bw}} \tag{4}$$

$$T_{pkt} = \frac{k}{R_b} \tag{5}$$

The lowest limit for the R_{bw} requirement can be determined by combining (2) and (3)

$$R_{bw} \geq \frac{2k}{T_{cycle} - 2T_{set} - T_{wake} - T_{pkt}} \tag{6}$$

The wake-up radio active time, η is given as the fraction

$$\eta = \frac{T_{listen}}{T_{cycle}} \tag{7}$$

4 Energy Consumption Analysis

The average energy dissipation per received packet can be computed under the premise that each node receives an equal number of packets on average and that a packet is received for $\frac{1}{\lambda}$ second. In the sensor node, dissipation occurs at four different parts,

$$E_{node} = \frac{P_{sleep}}{\lambda} + \eta \frac{P_{WURx}}{\lambda} + [p_{ACK \geq 1} + p_{FAK \geq 1}(N_{nodes} - 1)]E_{ACK1} + [\mu_{ACKx} + \mu_{FAK}(N_{nodes} - 1)]E_{ACKx} \tag{8}$$

Where $p_{ACK \geq 1}$ is probability that the sensor node sends at least one ACK packet, $p_{FAK \geq 1}$ is the probability that the sensor node sends at least one fake ACK packet, μ_{ACKx} is the anticipated number of acknowledgment retransmissions, μ_{FAK} is the anticipated number of retransmitted fake acknowledgement. The probabilities are derived and shown in Table 4.

The transceiver energy consumption during sleep mode is represented by the first term, the wake-up reception ($WURx$) energy by the second, the energy used to transmit

the first acknowledgment by the third, and the energy required for retransmission of the acknowledgment by the fourth.

In order to achieve optimal performance of the passive wake-up radio, the harvested energy, E_{EH} must be able to accommodate the power requirements of the wake-up radio power from the time it wakes up until it is back to deep sleep (T_{ACT}) such that it wakes up the main radio successfully. Meaning that the harvested energy must be higher than the second term of equation (8)

$$E_{EH} \geq \eta \frac{P_{WURx}}{\lambda} \quad (9)$$

Therefore, since the harvested energy is compensated for the WuR energy, the average energy dissipation by the node attached to a passive wake-up radio is

$$E_{node} = \frac{P_{sleep}}{\lambda} + [p_{ACK \geq 1} + p_{FACK \geq 1}(N_{nodes} - 1)]E_{ACK1} + [\mu_{ACKx} + \mu_{FACK}(N_{nodes} - 1)]E_{ACKx} \quad (10)$$

The probability and the number of fake acknowledgments $p_{FACK \geq 1}$ and μ_{FACKx} are defined based on per 'other node' in the network basis. They are therefore multiplied by the number of "other nodes," or the total number of nodes less one. Consequently, the energy usage for each acknowledgment is

$$E_{ACK1} = \Delta E_{WURx} + \Delta E_{Tset} + T_{pkt} \Delta P_{TX} \quad (11)$$

$$E_{ACKx} = (T_{WURx} + T_{WUC} + T_{set}) \Delta P_{standby} + \Delta E_{Tset} + T_{pkt} \Delta P_{TX} \quad (12)$$

Where the power increase in mode (x) relative to sleep mode is represented by $\Delta P_{(x)}$, i.e., $(P_{(x)} - P_{sleep})$ and $\Delta E_{(x)}$ is the energy (or power) dissipation or increase in mode (x) relative to sleep mode, i.e., $(E_{(x)} - E_{sleep})$

The average packet delay or latency time (T_{LAT}) in a node attached to a passive wake-up radio is the sum of the wake-up radio wake-up time (WuR T_{WAKE}), main radio wake-up time (T_{WAKE}) and the CCA duration, given as

$$T_{LAT} = WuRT_{WAKE} + T_{WAKE} + T_{CCA} \quad (13)$$

Where $WuRT_{WAKE}$ is determined based on the harvested energy E_{EH} and the wake-up reception power P_{WURx} up until the time the wake-up receiver is active.

5. MAC Layer Packet Analysis

The performance of the proposed passive wake-up radio protocol is described in this section. Recent IoT communication research have used similar probabilistic MAC modeling techniques to assess network reliability and retransmission dynamics under energy constraints (Rahman *et al.*, 2024; Ross, 2022). The MAC layer packet statistics for the probability utilized in equation (8) are calculated in order to run the simulations for the performance evaluation of the proposed protocol. The statistics are computed based on the selected simulation value of maximum wake-up call count, $N_{WUC(MAX)} = 3$. The detailed derivation of the MAC layer packets statistics is shown in the following section.

The following parameters are used to derive the MAC layer packet statistics: p_{fail} (Probability of failed packet), P_{fake} (Probability of fake wake-up) and N_{WUC} (number of wake-up call).

5.1 Wake-Up Calls Statistics

Table 2 is used to determine the probability distribution. The Maximum number of wake-up calls $N_{WUC(MAX)}$ is 3. The number of wake-up calls and acknowledgments is shown in the first two columns, while potential scenarios are listed in the third. The probability that the specified scenario will occur is shown in the fourth column. 'WUC' means a wake-up call is received, 'ACK' means an acknowledgement is received, 'OK' means that the WUC or ACK happened as it should be, 'FAIL' means that the WUC or ACK failed to happen as it ought to, and 'X' denotes a "do not care" scenario whereby, it doesn't matter whether the wake-up call is successful or not.

Table 2. WUC scenarios probability

#WUC	#ACK	Scenario	Probability
1	1	WUC OK, ACK OK	$(1 - p_{fail})^2$
2	1	WUC FAIL	$p_{fail}(1 - p_{fail})^2$
	2	WUC OK, ACK OK	
		WUC OK, ACK FAIL	
3	1	WUC X, ACK OK	$p_{fail}^2(1 - p_{fail})^2$
	2	WUC FAIL	
		WUC OK, ACK OK	
	3	WUC FAIL	
		WUC OK, ACK FAIL	
		WUC X, ACK OK	
3	WUC OK, ACK FAIL		
	WUC X, ACK FAIL		
	WUC X, ACK OK		

The probability is multiplied by p_{fail} and the number of possible scenarios is increased by 1 each time the number of WUCs is increased. Consequently, $p_{WUC(n)}$, the probability of n WUC transmissions, is

$$p_{WUC(n)} = n(1 - p_{fail})^2 p_{fail}^{n-1} \quad (14)$$

However, when maximum wake-up calls of $N_{WUC(MAX)}$ happens, an error occur for a probability of $p_{WUC(N_{WUC(MAX)WUC})}$. The error occurs because the transmitter quits after $N_{WUC(MAX)}$ transmissions, whether or not the WUC and ACK were correctly received. The error can be easily fixed by changing $p_{WUC(N_{WUC(MAX)})}$ to

$$p_{WUC(N_{WUC(MAX)})} = 1 - \sum_{k=1}^{N_{WUC(MAX)}} p_{WUC(k)} \quad (15)$$

Where k is the number of wake-up calls.

The expected value is defined to be (Ross, 2022)

$$\mu_X \stackrel{\text{def}}{=} \sum_{n=1}^{MAX(n)} X_n P_X(X_n) \quad (16)$$

5.2 Acknowledgement Statistics

According to table 2, the probability of n acknowledgments for each link configuration is provided by $p_{ACK(n)}$ as

$$p_{ACK(n)} = (1 - p_{fail})^2 \sum_{k=n-1}^{N_{WUC(MAX)}-1} p_{fail}^k \quad (17)$$

The given probability is only valid when the number of WUC transmissions has no maximum. Where the number of transmissions is limited, the approximation error is given as

$$p_{error} = (1 - p_{fail}) \cdot p_{fail}^{N_{WUC(MAX)}} \quad (18)$$

After this approximation error from (17) is corrected, the probability can be determined by

$$p_{ACK(n)} = (1 - p_{fail})^2 \sum_{k=n-1}^{N_{WUC(MAX)}-1} p_{fail}^k + (1 - p_{fail}) \cdot p_{fail}^{N_{WUC(MAX)}} \quad (19)$$

Using the well-known geometric series summation

$$\sum_{k=0}^n p^k = \frac{1 - p^{n+1}}{1 - p} \quad (20)$$

the $p_{ACK(n)}$ probability is simplified to

$$p_{ACK(n)} = (1 - p_{fail}) \cdot p_{fail}^{n-1} \quad (21)$$

The number of acknowledgements expected is calculated by substituting equation (21) into definition (16):

$$\mu_{ACK} = \frac{1 - p_{fail}^{N_{WUC(MAX)}}}{1 - p_{fail}} - N_{WUC(MAX)} \cdot p_{fail}^{N_{WUC(MAX)}} \quad (22)$$

The second term can be ignored since it is relatively much smaller when compared to the first term.

$$\mu_{ACK} \approx \frac{1 - p_{fail}^{N_{WUC(MAX)}}}{1 - p_{fail}} \quad (23)$$

When $N_{WUC(MAX)} = 1$, the approximation error is maximally p_{fail} , and it rapidly reduces as the number of retransmissions increases.

Because the transceiver is already in transmission mode, retransmitting an acknowledgment may require a different amount of energy than the initial transmission. Therefore, it is necessary to specify the probability that at least the first ACK packet will be sent $p_{ACK \geq 1}$ and the expected number of retransmissions μ_{ACK} . The former one is

$$p_{ACK \geq 1} = \sum_{n=1}^{N_{WUC(MAX)}} p_{ACK(n)} \quad (24)$$

which simplifies to

$$p_{ACK \geq 1} = 1 - p_{fail}^{N_{WUC(MAX)}} \quad (25)$$

Given by μ_{ACK} , the expected number of retransmissions is

$$\begin{aligned}\mu_{ACKx} &= \mu_{ACK} - p_{ACK \geq 1} \\ &= \frac{p_{fail}}{1 - p_{fail}} - p_{fail}^{N_{WUC(MAX)}} \left(N_{WUC(MAX)} + \frac{p_{fail}}{1 - p_{fail}} \right)\end{aligned}\quad (26)$$

The expected number of retransmissions while removing the second term, is

$$\mu_{ACKx} \approx \frac{p_{fail}}{1 - p_{fail}} \quad (27)$$

5.3 Fake Wake-up Statistics

A node starts sending fake acknowledgments (FACK) when it gets a wake-up call intended for another node and mistakenly thinks it is the destination. A maximum number of acknowledgements will be transmitted by the node. It also clogs the channel and uses a lot of power. Assuming that the number of fake wake-ups rises with network size, this section computes the expected number of fake acknowledgements per packet per "other node."

Table 3. Fake wake-up scenarios' probability

#WUC	#Fake ACK	Scenario	Probability
1	$N_{WUC(MAX)}$	FAKE	$P_{fake}P_{WUC,1}$
2	$N_{WUC(MAX)}$	FAKE, X	$P_{fake}P_{WUC,2}$
	$N_{WUC(MAX)} - 1$	OK, FAKE	$P_{fake}(1 - P_{fake})P_{WUC,2}$
3	$N_{WUC(MAX)}$	FAKE, X, X	$P_{fake}P_{WUC,3}$
	$N_{WUC(MAX)} - 1$	OK, FAKE, X	$P_{fake}(1 - P_{fake})P_{WUC,3}$
	$N_{WUC(MAX)} - 2$	OK, OK, FAKE	$P_{fake}(1 - P_{fake})^2P_{WUC,3}$

Probability that n fake ACKs are transmitted, expressed as $p_{FACK(n)}$ is determined from Table 3. The first column indicates how many wake-up calls were made. The scenario shown in the third column is where "OK" indicates that the packet is disregarded as it should be, 'FAKE' means a falsely decoded packet, and 'X' indicates a do not care. The probability of n fake acknowledgements based on the Table 3 is

$$p_{FACK(n)} = P_{fake}(1 - P_{fake})^{N_{WUC(MAX)} - n} \sum_{k=N_{WUC(MAX)}+1-n}^{N_{WUC(MAX)}} p_{WUC(k)} \quad (28)$$

If $p_{WUC(k)}$ is substituted into the above equation, then probability of receiving n fake ACK packets is

$$p_{FACK(n)} = P_{fake}(1 - P_{fake})^{N_{WUC(MAX)} - n} \frac{(1 - p_{fail})^2}{p_{fail}} \sum_{k=N_{WUC(MAX)}+1-n}^{N_{WUC(MAX)}} k p_{fail}^k \quad (29)$$

When the sum is calculated, the equation becomes cumbersome. Nevertheless, it can be seen that for $n = N_{WUC(MAX)}$ the probability is maximal

$$p_{FACK(N_{WUC(MAX)})} \approx P_{fake} \quad (30)$$

and the probability of this happening rapidly decreases as n decreases when $p_{fail} \ll 1$.

Per 'other node' in the network, the number of falsely transmitted acknowledgments according to definition (16) is

$$\mu_{FACK} = \sum_{k=1}^{N_{WUC(MAX)}} k \cdot p_{FACK(k)} \quad (31)$$

Since $p_{FACK(k)}$ is insignificant aside from $n = N_{WUC(MAX)}$ which can be represented approximately as

$$\mu_{FACK} \approx N_{WUC(MAX)} p_{fail} \quad (32)$$

Given $p_{FACK \geq 1}$, the probability of transmitting at least one fake acknowledgment is equal to

$$p_{FACK \geq 1} = \sum_{k=1}^{N_{WUC(MAX)}} p_{FACK(k)} \quad (33)$$

As stated earlier, $p_{FACK(k)}$ is gradually decreased as n decreases and its maximal for $n = N_{WUC(MAX)}$. Therefore, $p_{FACK \geq 1}$ can be approximated as

$$\begin{aligned}p_{FACK \geq 1} &\approx p_{FACK(N_{WUC(MAX)})} \\ &\approx P_{fake}\end{aligned}\quad (34)$$

Per 'other node' in the network, the expected number of fake acknowledgment retransmissions is



$$\mu_{FACKx} = (\mu_{FACK} - \mu_{FACK1}) \tag{35}$$

It has already been stated that the probability of $N_{WUC(MAX)}$ fake acknowledgments is higher than that of 1 fake acknowledgement. Therefore $\mu_{FACKx} \approx \mu_{FACK}$ and

$$\mu_{FACKx} \approx N_{WUC(MAX)} P_{fake} \tag{36}$$

Table 4 shows the MAC layer packet statistics and the corresponding probability values for the proposed passive wake-up protocol.

Table 4. MAC layer packet statistics

Statistic	Description	Probability
$P_{ACK \geq 1}$	Probability that the sensor node transmits at least one ACK packet.	$1 - P_{fail}^{N_{WUC(MAX)}}$
$P_{FACK \geq 1}$	Probability that the sensor node transmits at least one fake ACK packet.	P_{fake}
μ_{ACKx}	Average number of retransmitted acknowledgments per received packet.	$\frac{P_{fail}}{1 - P_{fail}}$
μ_{FACKx}	Average number of retransmitted fake acknowledgments per received packet and node in the network.	$P_{fake}(N_{WUC(MAX)} - 1)$

6. Simulation, Results and Discussion

The proposed algorithm was implemented by discrete-event simulations. To determine the efficiency of passive wake-up, the proposed method is simulated using the passive wake-up radio as well as the duty cycle scenario. The simulation results are then compared with other existing duty-cycled wake-up radio MAC protocols as benchmark. The simulation model consists of 5, 10 and 15 sensor nodes with one master node for each scenario. In the simulation, the Maximum number of wake-up calls, $N_{WUC(MAX)}$ is 3 and the packet rate, λ is 10 packets per second. Probability of failed packet p_{fail} as well as fake

wake-up P_{fake} are both 1%. The parameters specified in Table 5 are used to configure the simulated nodes. The radio power consumption parameters are obtained from previous works (Ghose *et al.*, 2018; Olleret *et al.*, 2016) and the nodes are setup based on the architecture in Figures 2 and 3. The wake-up call time T_{WUC} is set as 12.2 ms so as to facilitate judicious comparison with the benchmark scheme in the reference work (Ghose *et al.*, 2018; Olleret *et al.*, 2016). For the passive wake-up radio, it is assumed the energy harvested for each wake-up call is higher than the threshold given in equation (9).

Table 5. Simulation parameters

Parameters	Symbol	Value
Number of nodes	N	10, 15, 20
Data rate	R_{BW}	250 kbps
Voltage	V	3 volts
Active period	η	Passive, 20%, 50%
Wake-up reception power	P_{WURx}	2.4 mW
Reception power	P_{RX}	56.4 mW
Transmission power	P_{TX}	52.2 mW
Standby power	$P_{standby}$	60 μ W
Sleep power	P_{sleep}	10.5 μ W
Transition power	P_{Tset}	28 mW
Main radio wake-up time	T_{WAKE}	1.79 ms
CCA time	T_{CCA}	1.92 ms
Wake-up call time	T_{WUC}	(12.2, 6.3, 4.7) ms
Probability of failed packet	p_{fail}	1%
Probability of fake wake-up	p_{fake}	1%
Maximum number of wake-up call	$N_{WUC(MAX)}$	3

Initially, the proposed method was simulated under a passive wake-up radio scenario and then under a duty cycled wake-up radio scenario. The duty-cycled scenario is simulated using 20% and 50% duty cycle. The packet delivery ratio was unsatisfactory at lower duty cycles, so 20% was the minimum simulated. The results were then compared with the benchmark reference schemes (Ghose *et al.*, 2018; Olleret *et al.*, 2016).

6.1 Energy Consumption vs WuC Duration

It is evident from Figure 4 that lower energy consumption can be achieved by using shorter wake-up call durations. This is due to the fact that the WuC duration will decrease with increasing data rate. By reducing the WuC duration, it will result in less energy being consumed. A successful WuC transmission will require more retransmissions over a wider network, which will increase

energy usage. On the other hand, the energy required for WuC transmission is saved because both the benchmark protocol and the proposed protocol use CCA to check the channel occupancy state and continue sending the WuC if the channel is not idle. Until a WuC transmission is

successful or the attempt limit is reached, the same process will be repeated. This validates the reason for a gradual decline in the average energy consumed as the number of nodes N is increased.

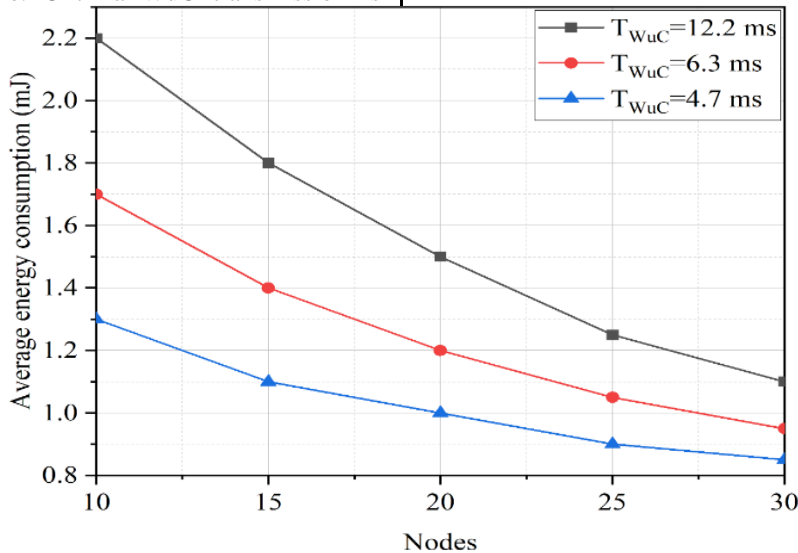


Figure 4. Effects of WuC duration on energy consumption

6.2 WuC Loss Probability

Figure 5 describe the effect of WuC duration on WuC loss probability. The WuC loss probability decreases as the WuC transmission data rate increases because greater data rates lead to shorter WuC durations. This is due to the fact

that a higher data rate results in a shorter WuC duration. Likewise, when the number of nodes (N) increases, the WuC loss probability rises monolithically. This is due to the fact that as the number of nodes (N) increases, so does the number of discarded (loss) packets.

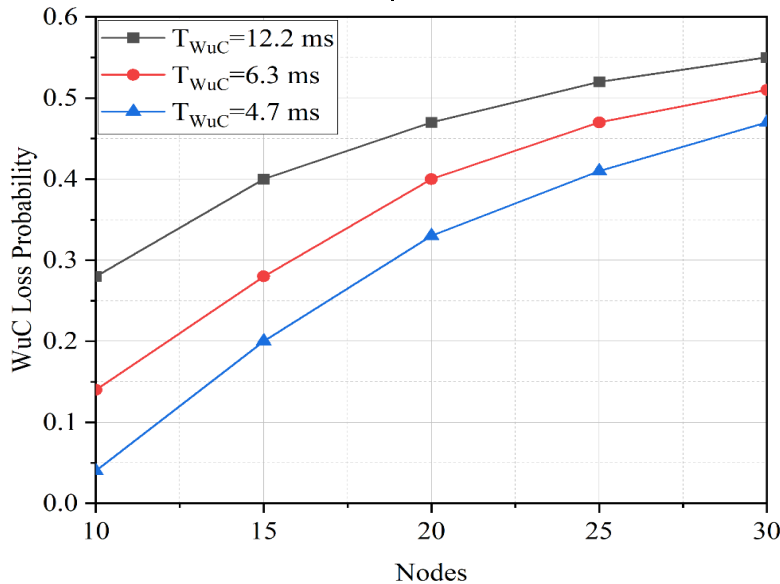


Figure 5. Effect of WuC duration on WuC loss probability

6.3 Passive vs Duty Cycle Comparison

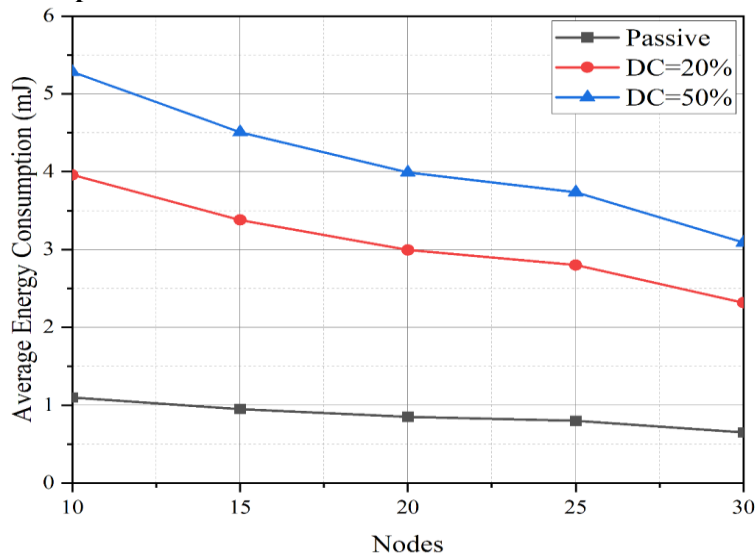


Figure 6. Average energy consumption comparison of passive wake-up protocol and duty cycle

Figure 6 shows the average energy usage of a passive wakeup network and a network with ordinary wakeup radios is shown for varying numbers of nodes. Because passive wakeup radio does not require synchronization or periodic activities, passive wakeup radio consumes a lot

less energy than the regular wakeup radio. The scenario with 50% duty cycle consumed higher energy than the scenario with 20% duty cycle. This is because, longer duty cycle time increases the active time of the nodes which results in higher energy consumption.

6.4 Comparison with Benchmark Protocols

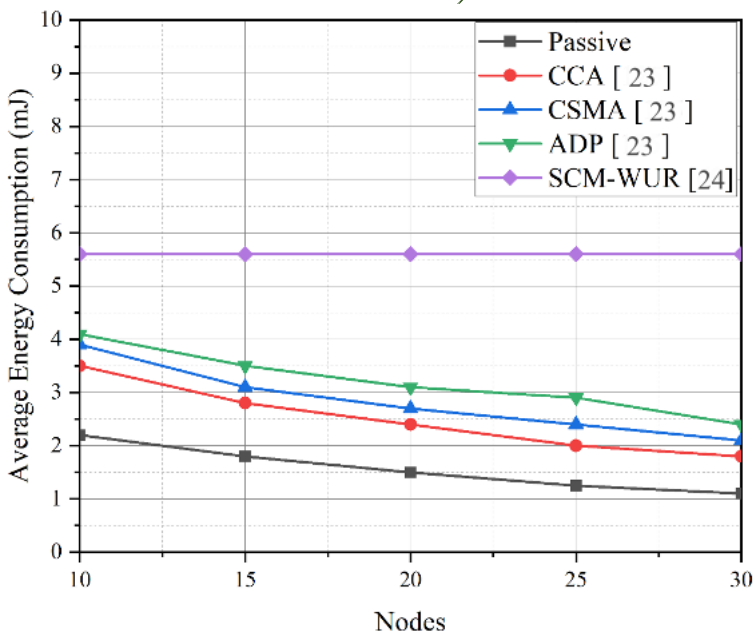


Figure 7. Comparison of average energy consumption of passive wake-up and benchmark protocols

Figure 7 illustrates the average energy consumption for passive wake-up network compared to other WuC MAC protocols under various network sizes. On the basis of the figure 7, it can be seen that the MAC protocol for passive wake-up radio is far less energy-intensive than all three benchmark protocols. It is apparent since the proposed

MAC protocol for passive wake-up radio stays in deep-sleep mode and only awakens when a wake-up signal is received. The SCM-WuR protocol consumes the most energy because for a WuC transmission to be successful or unsuccessful, each node must use almost the same amount of energy when using the protocol.

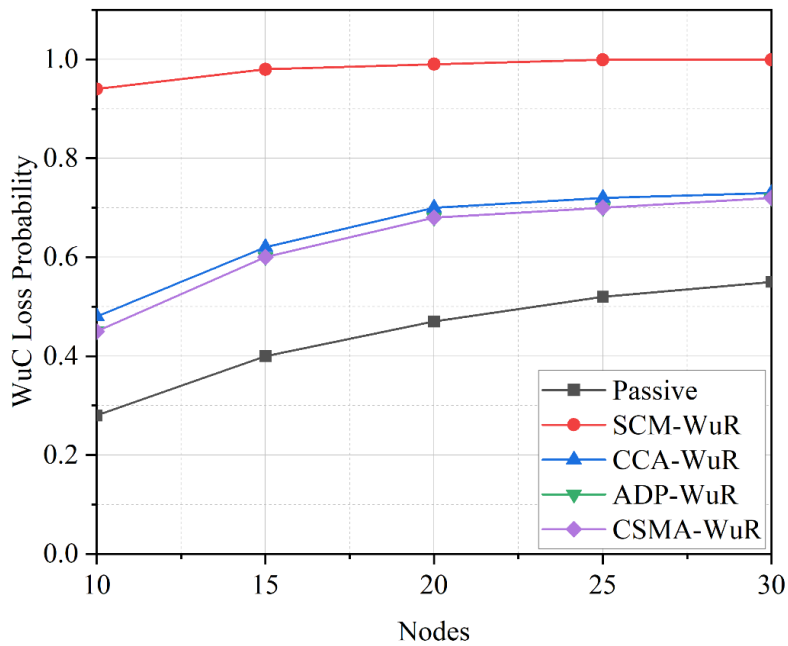


Figure 8. Comparison of WuC loss probability of passive wake-up protocol with benchmark protocols

Figure 8 shows how WuC loss probability varies as network size, N , changes. The WuC loss probability for each of the three proposed protocols outperformed that for the SCM-WuR protocol by a considerable margin. This is due to the fact that SCM-WuR does not feature a deferral method for transmitting WuC. Other protocols, however, enable an adaptive method before transmitting WuC, as a result, removing collisions. In addition to this, the proposed protocol reduces the WuC loss probability because the

WuC packets hardly miss the wake-up radio due to being in sleep mode from duty cycle as obtained in the other protocols. Thus, the proposed protocol can enable data transmissions with a higher degree of reliability. Meanwhile, as more nodes are added, the WuC loss probability increases. As network traffic loads increase, busy periods in the network become longer, resulting in lower WuC transmission probability. All protocols studied exhibit a similar trend as the network size grows.

6.5 Packet Delay Analysis

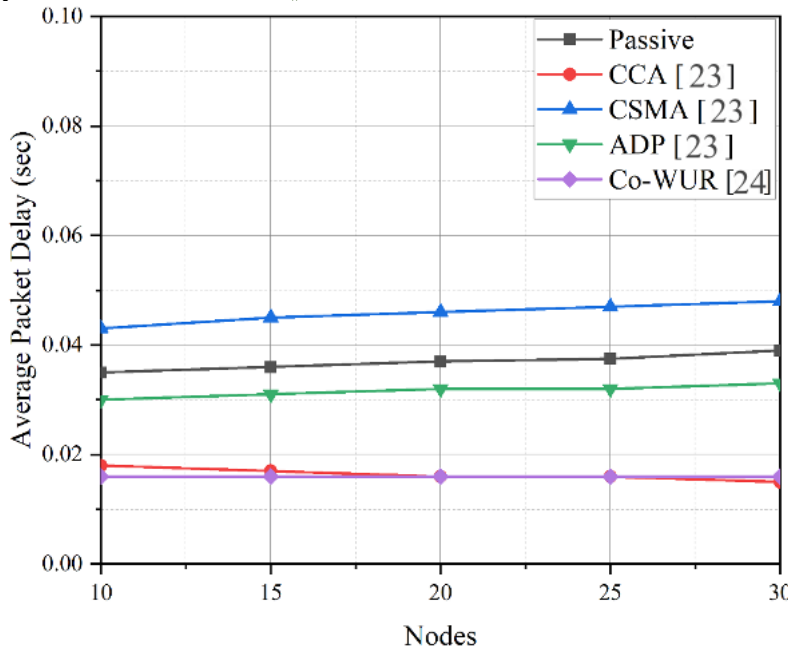


Figure 9. Average packet delay of passive wake-up and benchmark protocols

Figure 9 shows the average packet delay recorded during simulations of the passive wake-up radio protocol and other benchmark protocols as the number of nodes are

increased. Simulation results show that the passive wake-up network achieved a lower delay than the CSMA benchmark protocol. However, the proposed passive wake-



IJSGS FUGUSAU VOL. 12(1)

WEBSITE: <https://fugus-ijsgs.com.ng>

- | | |
|--|--|
| <p>approach optimized for low-latency IoT applications. <i>Sensors</i>, 22(23), Article 9429. doi.org</p> <p>Rahman, M. A., Islam, S. M. R., & Kim, D. (2024). Cross-layer optimization for energy-efficient IoT communications. <i>IEEE Access</i>, 12, 33450–33465. doi.org</p> <p>Ross, K. (2022). <i>An introduction to probability and simulation</i>. Bookdown. bookdown.org</p> <p>Sanchez-Iborra, R., et al. (2021). REFLOOD: Reactive routing protocol for wake-up radio in IoT. <i>Ad Hoc Networks</i>, 121, Article 102578. doi.org</p> | <p>Simeone, O., Erkip, E., & Shamai, S. (2022). Energy harvesting communications: Principles and challenges. <i>Foundations and Trends in Communications and Information Theory</i>, 19(1), 1–120. doi.org</p> <p>Yadav, R., Varshney, P. K., & Kumar, S. (2021). Performance analysis of MAC protocols in IoT networks. <i>IEEE Access</i>, 9, 107890–107905. doi.org</p> <p>Zhang, H., Liu, Y., & Wang, J. (2024). Low-power IoT communication protocols for smart environments. <i>IEEE Transactions on Green Communications and Networking</i>, 8(1), 210–222. doi.org</p> |
|--|--|