

Delay-aware energy-efficient slot scheduling medium access control for internet of things low-power networks

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ABSTRACT

The increasing deployment of internet of things (IoT) low-power networks (LPNs) introduce a fundamental challenge in achieving low-latency communication while maintaining strict energy constraints under dynamic and heterogeneous traffic conditions. Existing medium access control (MAC) protocols either rely on rigid time-division scheduling, leading to poor adaptability, or contention-based access, resulting in unpredictable delay and energy inefficiency. This paper proposes a delay-aware energy-efficient slot scheduling MAC protocol (IDAS-MAC), a lightweight and distributed framework that integrates priority-based scheduling, adaptive duty cycling, and hybrid slot management. The proposed approach introduces a novel two-hop contention-aware mechanism and modular arithmetic-based slot ownership to enable scalable, collision-aware, and delay-sensitive communication without centralized coordination. Unlike recent RL-based MAC protocols, the proposed scheme eliminates training overhead while maintaining adaptability to dynamic traffic patterns. Simulation results demonstrate that IDAS-MAC substantially reduces energy consumption and packet delay while improving throughput and processing efficiency compared with the considered conventional and recent MAC protocols. These results validate its suitability for energy-constrained and delay-critical IoT applications.

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1. INTRODUCTION

The rapid advancement of the internet of things (IoT) has enabled large-scale deployment of low-power sensing devices across diverse applications such as smart cities, healthcare, industrial automation, and environmental monitoring [1], [2]. These internet of things low-power networks (IoT-LPNs) consist of resource-constrained sensor nodes with limited battery capacity, processing capability, and communication range. At the medium access control (MAC) layer, efficient channel access scheduling plays a crucial role in ensuring reliable data transmission while minimizing energy consumption. However, achieving a balance between low-latency communication and energy efficiency remains a significant challenge, particularly in dynamic IoT environments where heterogeneous and priority-driven traffic is generated [3]-[15].

Conventional MAC protocols primarily follow either scheduled-based or contention-based approaches. Scheduled schemes such as time division multiple access (TDMA)-based protocols provide collision-free transmission and predictable latency but suffer from poor adaptability to dynamic traffic, which results in slot underutilization and increased delay [8], [15]. In contrast, contention-based protocols such as carrier sense multiple access with collision avoidance (CSMA/CA) offer flexibility and scalability but introduce unpredictable delays, collisions, and higher energy consumption due to idle listening and retransmissions [14]. Hybrid MAC protocols attempt to combine the advantages of both paradigms; however, they often lack efficient mechanisms for handling differentiated traffic priorities and dynamic scheduling in large-scale IoT-LPNs [3], [4].

Recent research has focused on enhancing MAC performance through energy-aware and intelligent scheduling mechanisms. Protocols such as quorum-based MAC (QZMAC) [5], and hybrid energy harvesting-based energy neutral operation MAC (HENO-MAC) [6] improve delay performance and energy neutrality under specific conditions but are limited in handling bursty traffic and scalable priority-based scheduling [16]-[18]. Other approaches emphasize clustering and cross-layer optimization to improve energy efficiency and connectivity [19], [20]; however, they often fail to address the trade-off between delay sensitivity and dynamic traffic adaptation. Furthermore, traditional quality of service (QoS)-aware MAC schemes provide differentiated services but introduce additional coordination overhead and limited scalability in dense deployments [21]-[23]. More recently, machine learning and reinforcement learning (RL)-based MAC protocols have been proposed to enable adaptive and intelligent scheduling decisions. Approaches such as deep reinforcement learning-MAC (DRL-MAC) [12] and RL-MAC [21], and artificial intelligence (AI)-driven MAC-Revivo [7] dynamically optimize channel access by learning network conditions over time. While RL-based MAC protocols [12], [21] provide adaptability, they incur high convergence overhead and computational cost. Similarly, quorum-based approaches such as QZMAC [5] suffer from idle listening, whereas TDMA-based schemes [15] lack flexibility under dynamic traffic. Additionally, learning-based approaches often lack interpretability and require continuous updates, which increases energy consumption and system complexity [24], [25].

Therefore, a critical research gap exists in developing a lightweight, delay-aware, and energy-efficient MAC scheduling mechanism that can effectively support heterogeneous traffic while maintaining low computational overhead. In particular, there is a need for a unified framework that integrates priority-based traffic differentiation, adaptive slot allocation, collision mitigation, and energy aware communication without relying on computationally intensive learning architectures.

To address these challenges, this paper proposes an integrated delay-aware scheduling mechanism for IoT MAC layer that combines the advantages of scheduled and contention-based paradigms in a unified framework. The proposed integrated dual-interval adaptive scheduling medium access control (IDAS-MAC) introduces a priority-weighted slot allocation strategy based on packet urgency and inter-arrival characteristics, enabling efficient handling of heterogeneous traffic. A distributed slot management mechanism based on modular arithmetic ensures scalable and conflict-free channel access without centralized coordination. In addition, a two-hop neighbour-aware contention window adaption mechanism is incorporated to reduce hidden terminal collisions and improve channel utilization. Furthermore, an adaptive transmission power control strategy based on received signal strength is employed to minimize energy consumption while maintaining reliable communication.

The novelty of IDAS-MAC lies not in introducing an isolated scheduling primitive, but in the coordinated integration of priority-aware slot allocation, adaptive duty cycling, two-hop contention control, and distributed modular slot ownership within a lightweight MAC framework. In comparison to QZMAC, which relies on quorum-based access and may incur additional idle listening, IDAS-MAC dynamically adapts slot access according to traffic urgency and local neighbourhood conditions. Unlike DRL-MAC, the proposed strategy does not require iterative learning, exploration, or convergence, thereby it avoids associated training and computational overhead. In comparison with MAC-Revivo, IDAS-MAC emphasizes more on deterministic distributed slot ownership and local two-hop contention awareness rather than coordination-intensive adaption. The resulting design thereby provides traffic-aware adaptability while it retains predictable rule-based slot access and lightweight implementation.

2. METHOD

2.1. Network model and assumptions

Consider an IoT-LPN with N sensor nodes uniformly and randomly deployed over a bounded 2D area. Each IoT node $i \in \{1, 2, 3, \dots, N\}$ is located at (x_i, y_i) and denoted using (1). The Euclidean distance between node i and j is computed using (2). Also, a binary link matrix $\epsilon_{\text{link}}(i, j)$ is defined using (3).

$$x_i, y_i \sim \mathcal{U}(0, A) \text{ where } i \in \mathbb{Z}^+ \quad (1)$$

$$d_{ij} \in \mathbb{R}^{N \times N} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (2)$$

$$\epsilon_{\text{link}}(i, j) = \begin{cases} 1 & d_{ij} \leq R \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

In (3) R refers to the communication radius. A fixed communication radius is used to provide a controlled connectivity model and to isolate the effect of the proposed scheduling strategy from variations caused by radio-range adaptation. This assumption is appropriate for the simulation-level evaluation of distributed slot ownership and two-hop neighbourhood constraints, while variable radio conditions remain and implementation consideration for future hardware validation. The node degree is also defined in (4). Let $h_i^{(1)}$ and $h_i^{(2)}$ denote the one-hop neighbours of i , respectively.

$$\text{deg}(i) = \sum_{j=1}^N \epsilon_{\text{link}}(i, j) \quad (4)$$

This network modeling step in the proposed framework establishes the spatial and connectivity foundation of the proposed framework by accurately capturing node distribution and link relationships. It enables local topology awareness (one-hop and two-hop neighborhoods), which is critical for distributed slot scheduling, collision avoidance, and scalability in IoT-LPNs. A uniform node deployment is adopted as a controlled baseline to avoid introducing application-specific spatial bias and to evaluate the intrinsic behaviour of the distributed scheduling mechanism under heterogeneous neighbourhood densities. Randomized placement also produces varying one-hop and two-hop neighbourhood structures, which are directly relevant to the proposed contention-aware scheduling strategy (Figure 1).

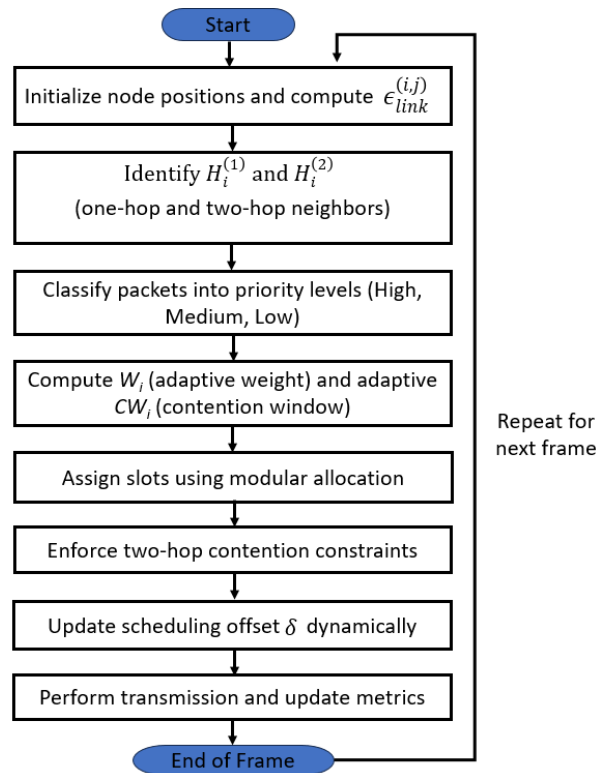


Figure 1. Workflow of the proposed IDAS-MAC scheduling algorithm

2.2. Frame structure and slot organization

In this framework time is divided into frames of duration T_{Frame} , where each contains F slots and can be modeled as (5):

$$T_{\text{Frame}} = T_{\text{SYNC}} + T_{\text{resv}} + T_{\text{data}} + T_{\text{ack}} \quad (5)$$

In (5) represents the total duration of a communication frame in the proposed IDAS-MAC scheduling scheme. Here each frame is divided into multiple time slots, and every slot is further segmented into four functional components. Here T_{SYNC} is used for exchanging synchronization information among nodes to maintain a common time reference which is essential for coordinated slot-based communication, T_{resv} refers to an interval in which nodes perform control signaling (e.g., RTS/CTS) to reserve slots for upcoming transmissions, thereby reducing collision probability. T_{data} on the other hand is the primary phase where actual data packets are transmitted between nodes. In this phase of T_{ack} receivers send acknowledgements (ACKs) to confirm successful data reception and ensure reliability. Here each node i is assigned with owned slot ($\text{slot}_i^{\text{own}}$) and coordination slot ($\text{slot}_i^{\text{c-slot}}$). Frame synchronization is maintained using local time of t_i^{frame} . In contrast to rigid TDMA schemes, the proposed structure enables: i) adaptive slot reuse, ii) hybrid contention and scheduling along with, iii) efficient idle-slot utilization. This approach overcomes underutilization issues observed in TDMA and reduces collision overhead seen in CSMA/CA. Here the integration of structured scheduling with controlled contention enables traffic-aware adaptability without incurring high coordination overhead, making the scheme suitable for dynamic IoT environments. The explicit separation of control and data phases also ensures predictable latency and improved reliability, which are often lacking in purely contention-based approaches. This hybrid design achieves balanced trade-off between determinism and flexibility, which is not effectively addressed in existing TDMA or CSMA/CA-based MAC protocols.

2.3. Priority-aware traffic modeling

Here each node maintains a queue Q where incoming packets are classified into three priority levels, high $P_{\text{high}}(i)$, medium $P_{\text{mid}}(i)$, and low $P_{\text{low}}(i)$. The packet arrival rate for node i is modeled in (6):

$$\lambda_i = P_i / T_f \quad (6)$$

Here λ_i refers to the packet arrival rate for node i (packets per second). P_i implies number of packets generated by IoT node i within a frame duration of T_f . Let A_i represents the ordered arrival sequence of packets, and Priority_i denote the scheduling indicator governing channel access. It has to be noted that unlike uniform traffic assumptions in MAC-Revivo, the proposed model captures heterogeneous and bursty IoT traffic patterns, enabling priority-driven scheduling and reduced queuing delay. Furthermore, it supports fine-grained service differentiation, ensuring that delay-sensitive packets are served with minimal latency. By incorporating stochastic arrival behaviour, the model improves robustness under dynamic traffic conditions while enhancing QoS provisioning without introducing additional control and computational overhead.

2.4. Delay-aware adaptive slot scheduling

The proposed scheduling mechanism assigns a dynamic weight to each node based on packet priority and traffic characteristics which is modeled in (7):

$$W_i = \alpha P_i + \beta / \Delta t_i \quad (7)$$

Here P_i implies packet priority level of node i , Δt_i refers to the inter-arrival time and α, β are weighting coefficients controlling the relative contribution of the corresponding traffic characteristics. This formulation prioritizes nodes with higher urgency and frequent arrivals. The contention window is adaptively-defined in (8):

$$CW_i = f(\lambda_i, \text{Priority}_i, \gamma) \quad (8)$$

Here λ_i refers to the packet arrival rate and γ is the scaling factor that controls contention aggressiveness. This formulation in proposed method enables delay-aware and traffic-adaptive scheduling without relying on RL, thereby eliminating training overhead, convergence delay and high computational complexity. Unlike, DRL-MAC, which depends on iterative learning and exploration, the proposed approach provides deterministic yet adaptive behaviour, ensuring predictable latency and stable performance. This makes it particularly suitable for resource-constrained IoT-LPN devices, where lightweight computation and real-time responsiveness are critical.

2.5. Two-hop contention control mechanism

To mitigate hidden terminal effects, slot allocation is considered such that no two nodes within two-hop neighborhood transmit in the same slot which is modeling in (9). The contention window is further refined based on local neighbourhood density as formulated in (10):

$$\forall j \in \mathcal{H}_i^{(2)}, \text{slot}_j^{\text{own}} \neq \text{slot}_i^{\text{own}} \quad (9)$$

$$CW_i = CW_{\min} + \gamma(N_{1,i} + wN_{2,i}) \quad (10)$$

where $N_{1,i}$ and $N_{2,i}$ represents the number of one-hop and two-hop neighbours of node i , respectively, γ is scaling factor whereas w is the weighting coefficient. Unlike conventional single-hop contention models, this approach explicitly incorporates two-hop neighbourhood awareness to effectively address hidden terminal problems. It significantly reduces collision probability and retransmissions by adapting the contention window to local network density. Furthermore, it also improves fairness and throughput by preventing overlapping transmissions in densely connected regions. This mechanism also provides lightweight and deterministic alternative to RL-based collision control, ensuring efficient performance without additional computational overhead.

2.6. Distributed slot assignment strategy

Slot ownership is determined using modular arithmetic to enable decentralized scheduling as shown in (11). Here ID_i is the unique identifier of node i , n_i is the number of neighbouring nodes, H_i is a hash-derived value and δ is an adaptive scheduling offset, and F denotes the total number of slots per frame. This formulation enables fully distributed and lightweight slot assignment without requiring centralized coordination and control signaling. The use of an adaptive offset δ helps in mitigating persistent slot conflicts under dynamic topology conditions. Unlike MAC-Revivo, which relies on coordination-intensive mechanisms, the proposed approach minimizes overhead while maintaining efficient slot utilization. This ensures high scalability for dense IoT-LPN deployments (100-400 nodes) with reduced collision probability and stable scheduling performance.

$$\text{slot}_i^{\text{own}} = ID_i \bmod n_i \quad (11)$$

$$S_i = (H_i + \delta) \bmod F \quad (12)$$

The modular formulation provides a deterministic mapping between node identity, neighbourhood information, scheduling offset, and available frame slots. Its role is therefore, not to claim modular arithmetic itself as a new mathematical operation, but to offer a lightweight mechanism for distributing slot ownership without maintaining a centralized allocation table. The adaptive offset further permits the assigned slot to be shifted when local contention conditions change. Therefore, the combination of deterministic slot indexing and adaptive offset reduces the need for repeated global coordination while it supports slot reuse in spatially separated regions. This design is particularly beneficial as node density increases because slot decisions can be delivered locally from node and neighbourhood information.

2.7. Energy consumption model

The total energy consumption of an IoT node is modeled using (13). Where transmission and reception energies are defined using (14). The energy consumed per successfully transmitted message is represented using (15). To further optimize the energy usage, adaptive transmission power control is applied as shown in (16):

$$E_{\text{Total}} = E_{\text{Tx}} + E_{\text{Rx}} + E_{\text{idle}} + E_{\text{sleep}} \quad (13)$$

$$E_{\text{Tx}} = P_{\text{tx}} \cdot t_{\text{tx}}, E_{\text{Rx}} = P_{\text{rx}} \cdot t_{\text{rx}}, \quad (14)$$

$$E_{\text{pbit}} = E_{\text{Total}} / n_{\text{msg}} \quad (15)$$

$$\xi_{\text{req}} = \xi_{\text{max}} / \xi_{\text{rec}} * \varepsilon_{\text{thres}} * k \quad (16)$$

where ξ_{rec} is the received signal strength, $\varepsilon_{\text{thres}}$ is the minimum required threshold, and k is a constant factor. This model jointly incorporates duty cycling and adaptive transmission power control, enabling significant reduction in transmission and idle listening energy while maintaining reliable communication. Unlike QZMAC, which suffers from energy loss due to idle listening, and DRL-MAC which incurs additional energy overhead from exploitation and learning, the proposed analytical model provides efficient energy optimization without computational complexity. This makes it well-suited for large-scale IoT-LPN simulations and practical low-power deployments.

2.8. Performance metrics

The performance of the proposed IDAS-MAC is evaluated using throughput and end-to-end delay. Throughput is defined as the total successfully received data within a frame duration is represented using (17). Here, T_{Frame} represents the duration of the communication frame. The end-to-end delay is also computed using (18).

$$\text{Throughput} = \frac{\sum \text{successfully recieved data}}{T_{\text{Frame}}} \quad (17)$$

$$D = \sum_{i=1}^N \left(L_i / R_i + Q_i \right) \quad (18)$$

Here L_i is the packet size of i , R_i is the data rate, and Q_i represents the queuing delay at node i . Here N is the number of evaluated packets. For example, if N_s packets of 18 bytes are successfully received during a frame of duration T_{Frame} , the throughput is $N_s \times 18 \times 8 / T_{\text{Frame}}$ bps. Similarly, if a packet experiences 2 ms of transmission-related delay and 3 ms of queuing delay, its corresponding end-to-end delay is 5 ms. These metrics capture both network efficiency and latency performance under varying traffic conditions. The integration of delay-aware scheduling and adaptive contention control ensures bounded delay and strong throughput, even under high node density. Unlike conventional MAC protocols that suffer from congestion and delay spikes, the proposed framework maintains consistent performance by minimizing re-transmissions and optimizing slot utilization, making it suitable for real-time IoT-LPN applications. The evaluation assumes a fixed packet size of 18 bytes, as specified in Table 1, while packet arrivals vary according to the configured inter-arrival conditions. Throughput therefore represents successfully delivered payload per unit time, whereas end-to-end delay includes transmission-related and queuing components experienced by successfully delivered packets.

Table 1. Simulation parameters

Parameter	Values
No. of IoT device	100-400
Transmission range (m)	20 m
Area of deployment (m ²)	100×100 m ²
Channel capacity	17 kbps
Transmit/receive power	38 mW/18 mW
Duty cycle	0.15
No. of slots	100
Simulation iterations	500
Data size	18 bytes
Initial battery energy	0.5 J

3. RESULTS AND DISCUSSION

3.1. Simulation setup

The proposed framework was implemented in MATLAB 2020b using the standard MATLAB computational environment. No specialized hardware accelerator or learning-specific toolbox was required because IDAS-MAC relies on lightweight mathematical scheduling operations rather than model training. The mechanism evaluated under realistic IoT-LPN conditions with node density varying from 100 to 400 nodes, ensuring scalability analysis. The simulation parameters are summarized in Table 1. The transmission range of 20 m is selected to represent short-range communication among resource-constrained IoT sensor nodes in low-power deployments, while providing a controlled neighbourhood structure for evaluating one-hop and two-hop contention. The 17 kbps channel capacity is adopted as a conservative low-data-rate setting representative of constrained IoT communication and is kept fixed across all protocols to ensure a fair comparison. The selected parameters are intended to provide a controlled representation of short-range, low-rate IoT-LPN communication rather than to reproduce a specific hardware platform. Prior IoT/WSN

MAC implementations and scheduling studies provide practical context for such constrained communication settings [3], [5], [20]. Hardware-specific radio characteristics are reserved for future validation.

The duty-cycle parameter is initialized at 0.15 as the baseline active-period constraint, while the proposed scheduling mechanism adaptively determines transmission opportunities and inactive periods according to traffic and contention conditions. To ensure fair and comprehensive benchmarking, the proposed method is compared against conventional MAC protocols such as ALOHA/CSMA-CA and TDMA and recent state-of-the-art protocols such as QZMAC, MAC-Revivo, and DRL-MAC. QZMAC, MAC-Revivo, and DRL-MAC were selected because they represent distinct recent MAC design directions relevant to the objectives of this study, including quorum-based access, adaptive/AI-assisted coordination, and learning-based scheduling, respectively. Their inclusion enables IDAS-MAC to be evaluated against different strategies for addressing energy efficiency, adaptability, and delay rather than against a single MAC design paradigm. Unlike prior works where comparisons are limited, this study aligns simulation conditions with reported configurations to ensure analytical consistency and fairness. Where implementations were available or sufficiently specified, the benchmark configurations were aligned with the corresponding reported operating conditions as far as possible, while common network-level parameters were kept identical across protocols to support controlled comparison. Differences arising from protocol-specific assumptions are acknowledged as part of the simulation-based evaluation.

The present study focuses on MATLAB-based simulation to isolate the MAC-layer scheduling behaviour under controlled network conditions. Hardware-level validation was not included in the current study; therefore, the reported energy values represent the analytical energy model defined in subsection 2.7 rather than direct measurements from physical devices. The simulation-based evaluation enables controlled comparisons across the considered MAC protocols while it avoids hardware-specific effects. The simulation incorporates randomized node/traffic realization via MATLAB's random-number functions. Since the present implementation does not impose a manually fixed random seed, the reported results represent the observations generated under the specified simulation configuration rather than a deterministic seed-controlled benchmark. To support reproducibility, the complete parameter configuration, network dimensions, traffic conditions, duty cycle, slot count, packet size, and energy parameters are explicitly reported in Table 1. For each evaluated inter-arrival condition, the performance values collected over the configured scheduling slots were aggregated and represented using their mean values. Hence, the energy and delay results correspond to the average of the observations generated during the existing simulation procedure rather than to a single instantaneous observation.

3.2. Energy efficiency and traffic-arrival sensitivity analysis

The energy performance of IDAS-MAC under varying packet inter-arrival conditions is shown in Figure 2. Figure 2(a) shows that the strategy consistently achieves lower energy consumption compared to ALOHA/CSMA and TDMA across all traffic conditions. Figure 2(b) shows that IDAS-MAC consistently maintains higher residual energy compared to ALOHA/CSMA and TDMA across all traffic conditions. The near-stable energy trend also indicates efficient resource utilization under varying traffic loads. It is also observed that QZMAC suffers from idle wake-ups whereas DRL-MAC incurs exploration overhead and MAC-Revivo incur high coordination cost whereas IDAS-MAC reduces energy by ~33-55% compared to recent protocols. The lower energy consumption of the proposed strategy can be attributed to the interaction of three mechanisms. Firstly, the priority-aware slot selection minimizes unnecessary waiting for delay-sensitive packets. Secondly, adaptive duty cycling limits prolonged active periods when transmission opportunities are unavailable. Thirdly, two-hop contention awareness significantly reduces overlapping transmissions and the associated re-transmissions. Therefore, the energy advantage is not attributed to a single scheduling component but to the combined reduction of active, collision-related, and retransmission-related energy expenditure. The relatively stable trend across inter-arrival conditions further implies that these strategies do not introduce substantial additional energy overhead as traffic conditions vary.

To examine sensitivity to traffic-generation conditions, the packet inter-arrival parameter was varied from 1 to 10 scheduling units under the same network and MAC configuration. This variation represents different traffic-generation frequencies and allows the robustness of the proposed strategy to changing traffic intensity to be assessed without modifying the underlying protocol configuration. As shown in Figure 2, IDAS-MAC maintains a comparatively stable energy profile across the evaluated inter-arrival range, which implies that the combination of adaptive duty cycling, priority-aware scheduling, and contention control remains effective under varying traffic conditions. Channel-error sensitivity was not explicitly modeled in the present simulation and thereby represents an important direction for future evaluation, particularly for interference-prone wireless environments.

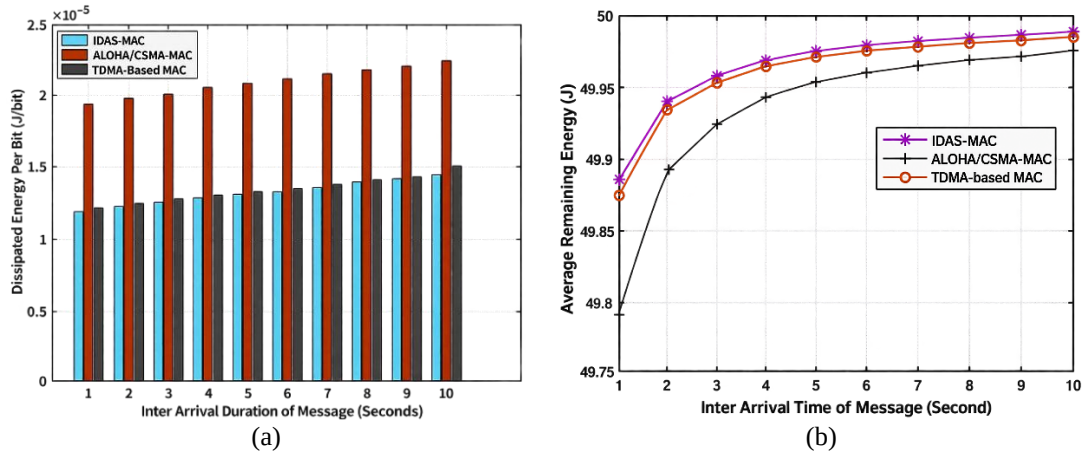


Figure 2. Energy performance of IDAS-MAC under varying packet inter-arrival conditions: (a) energy consumption per bit and (b) average remaining energy compared with baseline and recent MAC protocols

3.3. Average end-to-end delay analysis

Figure 3 shows that the proposed framework consistently achieves lowest end-to-end delay as network size increases from 50 to 400 nodes. While ALOHA/CSMA exhibits the highest delay due to collisions and contention, and TDMA suffers from rigid slot allocation, recent approaches such as QZMAC, MAC-Revivo, and DRL-MAC also experience increasing delay under higher node density.

In contrast IDAS-MAC maintains significantly lower delay due to its delay-aware scheduling, two-hop contention control and adaptive slot allocation. The relatively slower growth in delay demonstrates its scalability and effectiveness in handling dense IoT-LPN deployments. The general simulation configuration considers 100–400 IoT devices, while the scalability analysis in Figure 3 additionally considers a 50-node case to illustrate low-density network behaviour. It has to be noted that to address the scalability concerns performance was also evaluated with increasing node density. It can be seen that delay remains bounded across the evaluated range up to 400 nodes. Beyond the evaluated range of 400 nodes, increasing neighbourhood density may increase two-hop topology information, local contention, and synchronization overhead, which could gradually reduce the efficiency of distributed slot reuse. Therefore, performance beyond 400 nodes should be interpreted as an open scalability boundary rather than assumed to remain unchanged, and larger-scale evaluation is considered future work. Also, it exhibits stable delay without sudden spikes. DRL-MAC shows higher delay due to convergence time. The prime reason that IDAS-MAC reduces delay due to priority driven scheduling (high priority packets get faster access), two-hop contention control which minimizes retransmissions and deterministic slot assignment which avoids random delays.

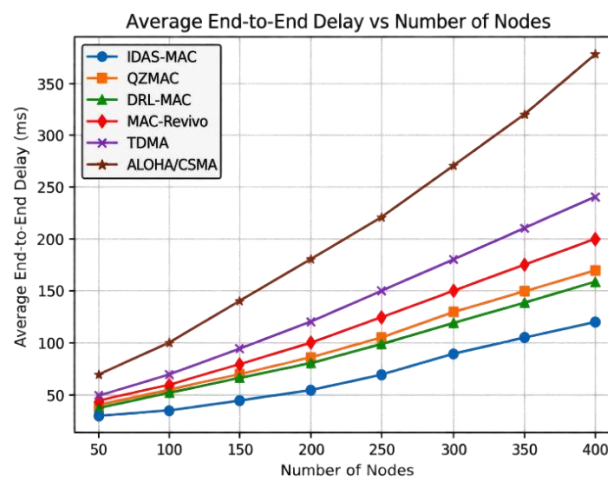


Figure 3. Average end-to-end packet delay of IDAS-MAC and competing MAC protocols as a function of IoT node density

The delay reduction can be interpreted from the local contention structure. In a single-hop contention strategy two nodes that cannot directly detect each other may yet transmit simultaneously toward a common neighbour, which causes collisions and re-transmissions. The presented two-hop constraint accounts for this local interference relationship before slot use, therefore it reduces the probability of repeated transmission attempts. In combination with priority-aware access, this reduction in retransmission-induced waiting time directly contributes to the lower end-to-end delay as observed in Figure 3. The scalability behaviour is also related to the distributed slot ownership mechanism. Because slot selection is derived locally from node identity, neighbourhood information, and the adaptive scheduling offset, the protocol doesn't require a centralized scheduler to re-compute the complete slot map as node density increases. The resulting local decision process limits coordination overhead and helps explain the comparatively gradual increase in delay as the number of nodes grows.

3.4. Extensive throughput analysis

Figure 4 shows that IDAS-MAC achieves the highest throughput across the evaluated network sizes. At 200 nodes, IDAS-MAC achieves approximately 1080 kbps, compared with approximately 940 kbps for DRL-MAC, 900 kbps for QZMAC, and 880 kbps for MAC-Revivo. With increasing node density, the throughput of IDAS-MAC continues to increase gradually and reaches approximately 1180–1200 kbps at 400 nodes. In contrast, the competing approaches exhibit slower growth or saturation under higher contention. The numerical values represent mean results obtained under the representative simulation configuration used for comparative evaluation, whereas the feature columns summarize the principal architectural characteristics of each protocol. The benchmark implementations were configured to provide comparable network and traffic conditions.

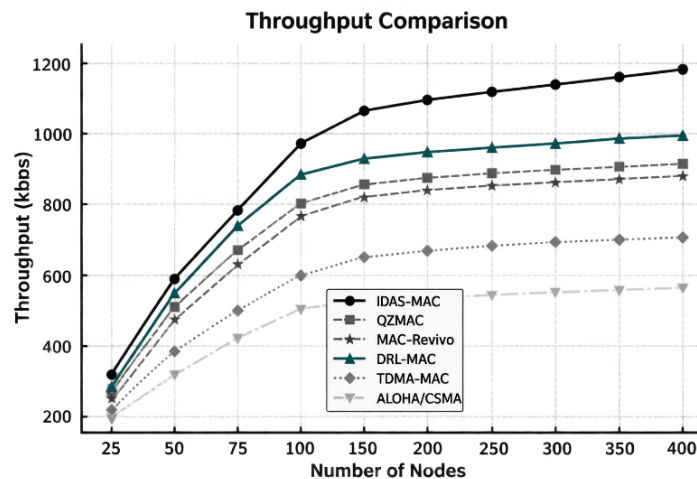


Figure 4. Comparative throughput of IDAS-MAC and existing MAC protocols under increasing IoT-LPN node density

Table 2 also highlights that unlike DRL-MAC, IDAS-MAC avoids training and convergence overhead and also uses lightweight analytical scheduling which makes it suitable for resource-constrained IoT devices. It has to be noted that the results are reported using mean values which are obtained from the collected simulation observations. The observed variation across inter-arrival conditions and network sizes is additionally discussed to characterize the stability of the proposed mechanism. Because the current implementation was designed as a controlled simulation study rather than a repeated Monte Carlo experiment, confidence intervals and inferential significance tests are not reported. The reported values represent mean observations collected under the specified simulation configuration. Statistical uncertainty across independently repeated simulation seeds will be investigated in future work. Overall, the results indicate a favourable energy-delay-throughput trade-off.

It has to be noted that the initial energy of each node is set to 0.5 J, whereas the energy values reported in Table 2 represent the aggregate energy consumption obtained from the simulation. The reduction in delay is obtained primarily through priority-aware access and reduced collision/re-transmission events, whereas adaptive duty cycling limits the energy cost associated with maintaining channel availability. At the

same time, improved slot utilization allows more successful packets to be delivered, which result in higher throughput. These observations indicate that the proposed improvement in one metric does not arise solely from sacrificing another, rather the coordinated scheduling mechanisms contribute jointly to the observed performance balance.

Table 2. Quantitative and qualitative comparison of IDAS-MAC with existing IoT MAC protocols

Protocol	Priority-aware scheduling	Two-hop contention	Distributed slot allocation	RL/training	Energy (J)	Delay (ms)	Processing time (s)
IDAS-MAC	✓	✓	✓	No	0.8	20	1.2
QZMAC [5]	Limited	–	Quorum-based	No	1.6	45	2.3
MAC-Revivo [7]	Adaptive	–	Coordination-based	No/AI-based	1.4	38	2.0
DRL-MAC [12]	✓	–	Learning-based	✓	1.9	50	3.5

Note: quantitative values correspond to the 200-node configuration under the specified traffic condition and represent mean simulation observations.

Despite the observed improvements, the proposed strategy has several limitations. Firstly, the evaluation is simulation-based and therefore does not capture all hardware-specific effects such as clock drift, radio transceiver variability, channel fading, and implementation dependent synchronization errors. Secondly the two-hop neighbourhood mechanism introduces additional local topology information requirement, which may increase control overhead in extremely dense networks. Third, the current evaluation considers a fixed transmission range, and controlled duty cycle configuration, therefore, performance under highly dynamic channel conditions and heterogeneous radio capabilities require further investigation. These limitations do not affect the internal comparison performed in the present study but define the scope for future hardware-based validation.

The simulation results consistently implies that IDAS-MAC provides a balanced improvement across energy consumption, packet delay, throughput, and processing time under the evaluated configurations. The observed gains are primarily associated with priority-aware access, reduced two-hop contention, adaptive slot utilization, and lightweight distributed scheduling. The results also show that the protocol retains stable behaviour as network density increases, which supports its suitability for delay-sensitive energy-constrained IoT-LPN scenarios. IDAS-MAC is positioned as a lightweight scheduling mechanism for IoT-LPN MAC operation rather than as a replacement-level implementation of a complete standard stack. In comparison with standardized scheduled approaches such as IEEE 802.15.4-based operation and 6TiSCH, the present work focuses specifically on priority-aware distributed slot management, two-hop contention mitigation, and adaptive duty-cycle operation. A direct quantitative comparison with complete standard implementations is outside the scope of the present simulation and is therefore identified as future work. The proposed operations consist primarily of local neighbour identification, priority evaluation, arithmetic slot computation, contention-window adjustment, and energy estimation, making the scheduling logic computationally lightweight. Therefore, the protocol is conceptually compatible with resource-constrained IoT hardware; however, implementation-specific factors such as clock synchronization, memory availability, radio-state switching, and transceiver power characteristics should be evaluated through hardware experiments in future work.

4. CONCLUSION

The paper introduces IDAS-MAC, an integrated delay-aware scheduling MAC protocol designed for energy-constrained IoT LPNs. IDAS-MAC offers an integrated MAC-layer design combining delay-aware scheduling, adaptive duty cycling, two-hop contention control, and distributed slot management. The aim of the proposed work was to strategically combine delay-awareness, duty-cycling, and slot management into a cohesive MAC-layer design tailored for LPNs. Through a joint slot management and contention-aware MAC design, it effectively balances energy efficiency, latency, and reliability under dynamic traffic conditions. From an application perspective, the lightweight scheduling design is particularly relevant to IoT deployments in which delay-sensitive events coexist with routine sensing traffic, such as environmental monitoring, industrial monitoring, and healthcare sensing. Priority-aware access can provide faster service to urgent measurements while allowing regular sensing traffic to use remaining communication opportunities. The absence of iterative learning also reduces the computational requirements for resource-constrained sensor nodes. These improvements validate protocols effectiveness in enhancing energy suitability, delay minimization, and system responsiveness. Future work will focus on hardware-based prototyping and empirical energy validation using resource-constrained platforms such as the nRF52840,

together with cross-layer integration with routing and application-layer mechanisms. Larger-scale evaluations beyond 400 nodes and experiments under variable channel conditions will also be considered to further assess scalability and deployment robustness. In the longer term, the lightweight, distributed, and priority-aware design of IDAS-MAC may provide a practical basis for incorporating adaptive delay- and energy-aware scheduling principles into future IoT MAC implementations and standardization efforts.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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- C : Conceptualization
M : Methodology
So : Software
Va : Validation
Fo : Formal analysis
- I : Investigation
R : Resources
D : Data Curation
O : Writing - Original Draft
E : Writing - Review & Editing
- Vi : Visualization
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P : Project administration
Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

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

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