

Joint routing and clustered medium access control scheduling for energy-aware internet of things data dissemination

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ABSTRACT

Efficient data dissemination in large-scale internet of things (IoT) networks remain challenging due to energy constraints, congestion, and delay under dynamic network traffic. This paper introduces a joint routing and medium access control (MAC)-layer scheduling framework (JRSM), incorporating priority-aware clustering to enhance energy efficiency and reduce latency in the IoT data acquisition layer. The proposed design uniquely combines both link and broadcast scheduling with priority-aware clustering and adaptive slot allocation, ensuring collision-free transmission for high-priority, medium priority and regular traffic while maintaining optimal energy consumption. A graph-based shortest-path routing strategy is employed to optimize path selection with minimal operational cost, while MAC scheduling ensures efficient radio resource allocation and two-hop collision avoidance. Simulation results clearly demonstrates that JRSM improves average remaining energy by approx. 2% compared to sensor MAC (S-MAC) and approx. 2.2% compared to quality of service-aware MAC (Q-MAC), reduces energy dissipation by 43% versus S-MAC and 4% versus Q-MAC, and lowers average packet latency by 26.5% compared to S-MAC and 19.3% compared to Q-MAC, highlighting its effectiveness in balancing energy efficiency and delay performance in IoT networks.

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1. INTRODUCTION

The internet of things (IoT) connects heterogeneous sensing and computing devices to support distributed data acquisition and communication across applications such as agriculture, healthcare, industrial automation, and environmental monitoring [1]–[5]. Wireless sensor networks (WSNs) constitute an important component of IoT data acquisition layer, where resource-constrained sensor nodes communicate with gateways via single or multi-hop links. However large-scale deployments face persistent challenges associated with limited energy resources, congestion, and communication delay, particularly under heterogeneous and variable traffic conditions [3]–[7].

Traditional WSN routing approaches face scalability, energy, and delay limitations in large IoT deployments [6], [7]. IoT-specific routing protocols which include recognition of prior learning (RPL) and its extensions such as enhanced RPL (EM-RPL), ELITE, ARMOR, dynamic decision system based on learning

automata RPL (DDSLA-RPL), and mobile RPL (MobiRPL) [8]–[12], improve routing reliability and adaptability but do not simultaneously optimize energy, congestion, and delay under heterogeneous traffic. Cognitive nature-inspired and reinforcement learning-based routing methods [6], [13] can improve path selection and energy balancing but their computational requirements may limit deployment on resource-constrained devices. Blockchain and software-defined networking (SDN)-assisted approaches [14], [15] improve adaptability and reliability but introduce additional implementation overhead and generally do not jointly optimize routing and medium access control (MAC) scheduling. A critical survey of recent literature also indicates that most of the IoT studies either focus on routing optimization or MAC-layer scheduling, rarely addressing both. Traditional routing protocols lack integrated scheduling to control congestion and delay. MAC-layer scheduling strategies in IoT play a critical role towards managing contention, collision, and radio-resource allocation among IoT nodes. Jiang *et al.* [16] and Selem *et al.* [17] introduced time division multiple access (TDMA)-based frameworks to offer energy-efficient channel access but often neglect delay-sensitive traffic and do not adaptively differentiate between high-priority and normal data. It is also observed that recently sensor MAC (S-MAC) [18], [19] and quality of service-aware MAC (Q-MAC) [20] have been widely adopted as baseline scheduling approaches due to their ability to reduce energy consumption and enhance throughput. Sadeq *et al.* [18] proposed a conceptual IoT-MAC framework that aims to enhance energy efficiency, building upon S-MAC principles such as duty cycling and collision avoidance. On the other hand, Acik and Kosunalp [19] evaluated energy-efficient MAC protocols including S-MAC across terrestrial, unmanned aerial vehicle-assisted (UAV-assisted)-assisted and underwater IoT, but their focus remains limited to environmental adaptations rather than joint routing and scheduling, leaving a gap in energy-delay trade-offs in dense IoT networks. Zeb *et al.* [20] also presented energy-efficient cluster formation in IoT-enabled WBANs leveraging cluster-based scheduling to optimize energy consumption which is conceptually similar to Q-MAC's MAC layer scheduling for collision free transmissions. Even though S-MAC [18], [19] and Q-MAC [20] implements link and slot-based strategies to reduce collisions and energy use but do not optimize path selection or consider joint routing or dissemination. Other studies have also attempted hybrid solutions such as TDMA-based scheduling with linear programming [16], MAC-layer enhancements for industrial IoT [17], and cross-layer approaches for congestion mitigations [21], [22]. Existing IoT routing and MAC scheduling approaches suffer from three key limitations: lack of joint optimization of routing and scheduling, inability to efficiently handle heterogeneous traffic priorities (including medium-priority traffic), and high computational overhead in large-scale deployments.

Recent intelligent networking approaches further employ reinforcement learning, federated optimization, and graph neural networks for adaptive routing, resource allocation, and distributed decision-making. These methods can provide strong adaptability under dynamic network conditions, but generally require model training, additional computational resources, or distributed model-exchange mechanisms that may increase implementation complexity for resource-constrained IoT nodes. Joint routing and scheduling management (JRSM) instead adopts a lightweight graph-based routing and analytical scheduling strategy, prioritizing computational simplicity and predictable operation. Accordingly, the present work does not claim superiority over learning-based approaches in adaptability; rather, it provides a low-complexity alternative that jointly addresses routing and MAC scheduling. A direct experimental comparison with AI-assisted approaches will be considered after implementation of the corresponding learning-based baselines.

To address these limitations, this paper proposes a JRSM that tightly integrates energy-aware routing, priority-aware clustering, and adaptive MAC scheduling within a unified framework. The integration is intended to improve the energy-delay trade-off while maintaining differentiated service for high, medium, and normal-priority traffic with lower computational requirements than more complex learning-based approaches. Unlike existing hybrid or cross-layer approaches, which often introduce significant computational overhead or loosely coupled routing and MAC operations, JRSM performs tightly integrated and simultaneous optimization of routing and MAC scheduling with priority-aware clustering. Additionally, it uniquely incorporates medium-priority traffic handling, which is often neglected in existing IoT MAC protocols. This enables efficient energy-delay trade-offs in dense IoT networks with low computational complexity.

Compared with learning-based and more complex cross-layer approaches, JRSM is designed to reduce computational requirements by relying on graph-based routing and analytical scheduling rather than iterative model training. Extensive numerical simulation demonstrates that JRSM outperforms existing popular MAC-based approaches like Q-MAC and S-MAC in residual energy, average energy dissipation in Joule, and average packet latency. S-MAC and Q-MAC are chosen as representative baseline MAC-layer scheduling approaches due to their wide adoption in IoT-research, while other scheduling approaches were excluded due to high computational overhead or limited scalability in large-scale deployments. This joint

optimization enables JRSM to achieve balanced energy-delay performance across heterogeneous traffic, making it suitable for dense and resource-constrained IoT deployments.

The key contributions of this paper include the joint optimization of IoT routing and MAC-layer scheduling to achieve a balanced trade-off between energy consumption, latency and operational cost. The proposed framework incorporates priority-aware clustering to ensure timely delivery of high-priority traffic while maintains fairness for medium and normal traffic. An analytical energy-delay trade-off model based on shortest-path routing is employed to minimize operational cost while explicitly balancing energy and latency. Furthermore, the design is computationally efficient and suitable for large-scale, resource constrained IoT networks. Extensive performance evaluation demonstrates significant improvement in energy efficiency and delay reduction compared to baseline MAC scheduling protocols.

The design characteristics of JRSM make it applicable to several IoT scenarios where energy efficiency and timely data dissemination are important. In smart cities and intelligent transportation systems, priority-aware scheduling can support delay-sensitive messages, while industrial IoT applications can benefit from coordinated communication under dense device deployments. In precision agriculture, energy-aware multi-hop routing can extend sensor operation, whereas healthcare monitoring can use differentiated priority handling for time-sensitive physiological data. These application mappings represent the intended deployment relevance of the framework, while platform-specific validation remains part of future work.

The reminder of the paper is organized as follows: section 2 further illustrates the detailed research method along with workflow design modeling whereas section 3 analyses the simulation results and discussion. Section 4 finally concludes the presented research with future directions.

2. METHOD

2.1. Methodological overview of joint routing and medium access control scheduling

In the proposed work, the joint routing and scheduling method integrates routing optimization with MAC-layer scheduling to address three critical challenges in IoT-enabled WSNs viz: i) energy imbalance due to non-uniform data load, ii) congestion-induced latency under variable traffic, and iii) scalability limitations caused by static routing-scheduling coupling. Here the design adopts an analytical-numerical modeling approach that combines cost-effective graph-theoretic routing and adaptive radio-resource scheduling to ensure reliable, energy-aware, and priority-sensitive communication. Unlike conventional popular MAC scheduling frameworks such S-MAC or Q-MAC that solely operates at the IoT MAC layer, the proposed system jointly exploits link-layer contention control and network-layer routing to optimize the data dissemination. Here the framework also differentiates high, medium and normal priority traffic via dynamic slot adjustment and cluster-level synchronization, while ensure fairness and delay minimization across heterogeneous IoT applications. This tight integration differentiates JRSM from conventional cross-layer designs that treat routing and scheduling sequentially rather than jointly. The Figure 1 exhibits the methodological workflow that comprises of five critical stages. The overall workflow implicitly captures routing and scheduling steps, ensuring reproducibility without additional algorithmic overhead.

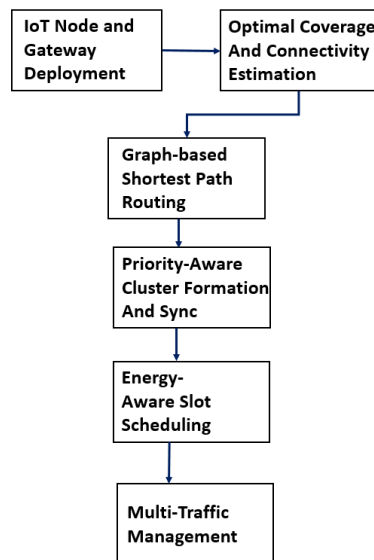


Figure 1. Methodological workflow

2.2. Internet of thing network initialization and deployment modeling

Let the deployment area (A_d) host N_{IoT} devices which are randomly positioned with coordinates (x_i, y_i) . Here the deployment ensures uniform random distribution to maintain coverage uniformly and connectivity balance while avoid spatial clustering. Here the IoT gateway's coordinates are represented with $(x_{G_{IoT}}, y_{G_{IoT}})$. Here each node i operates with a sensing radius (r_i) and communication radius (R_c), while the gateway node G_{IoT} is strategically localized within A_d for optimal reachability. In order to preserve the connectivity and avoid partitioning, the proposed JRSM computes optimal communication radius (R_c^*) by maintaining a neighbour threshold of (τ_N) within $[R_{min}, R_{max}]$. Here computation enables a distance function of $f_d(i, j)$ that evaluates Euclidian separation between node i, j . The communication graph as formulated $G(v, E)$ is generated where each vertex v_i represents IoT device and edges $E(i, j)$ are established if $(i, j) \leq R_c^*$. The total link set L_{tot} is computed using (1):

$$L_{tot} = \sum_{i=1}^{N_{IoT}} C_L(i) \quad (1)$$

Here $C_L(i)$ refers to the valid communication links for node i and the deployment ensures minimum link redundancy and maximum connectivity stability while maintains energy-balanced topology growth as the network scales.

2.3. Optimal routing with energy-delay trade-off

In the proposed framework, the routing process is computationally modeled as weighted directed graph $G(v, E, w)$. Here the edge weights w_{ij} represents composite cost metrics that involves the Euclidian distance, transmission energy, and residual energy ratio. JRSM formulates an adaptive, graph-theoretic routing model that minimizes the path cost while also preserve energy balance. Here each IoT sensor identifies its neighbour based on R_c^* and forms the connectivity matrix in the form of $d_M \in \{0, 1\}$. For any node-gateway pair (i, G_{IoT}) , the Euclidian distance is computed as $E_d(i, G_{IoT})$. If $E_d(i, G_{IoT}) < R_c^*$ then the connectivity is established with gateway, otherwise multi-hop routing is initiated. The routing process also enables a function of $\varepsilon_R(i, G_{IoT})$ that generates an optimal path P_o and associated cost ϕ using (2). Here each link e in the graph is weighted using $F_w: e \rightarrow \mathbb{R}^+$, and the total path length is computed using (3).

$$[P_o, \phi] \leftarrow \varepsilon_R(L_v, v_c) \quad (2)$$

$$L(P_o) = \sum_{i=1}^k w(e_i) \quad (3)$$

Here this dynamic weighting minimizes energy-intensive hops and helps balancing traffic across multiple routes and also helps reducing both congestion and delay. Compared to conventional EM-RPL and reinforcement learning (RL)-based routing JRSM's sequential computation mechanism accomplishes faster convergence with reduced memory overhead due to its lightweight iterative logic. Here the energy-delay cost function is modeled using (4):

$$\Theta(i, j) = \alpha \cdot \frac{E_{tx}(i, j)}{E_{res}(i, j)} + \beta \cdot D_{hop}(i, j) \quad (4)$$

Here $E_{tx}(i, j)$ refers to the energy required for transmission, $E_{res}(i, j)$ is the residual energy, and $D_{hop}(i, j)$ implies the hop delay. The weighting coefficients determine the relative contribution of the energy, residual-energy, and delay terms in the composite routing cost and were kept fixed across all simulation scenarios to ensure consistent comparative evaluation. The IoT routing formulates a shortest path tree using an enhanced Dijkstra's algorithm [23]–[25] that incorporates $\Theta(i, j)$ and yields optimal paths of P_o which minimizes both energy cost and end-to-end latency. Unlike conventional energy models, the proposed framework employs joint energy-delay objective that optimizes link utilization and traffic flow even under congestion. The computational complexity of the routing component is $O(E \log V)$, while scheduling operates in linear time with respect to cluster size, which ensure scalability.

2.4. Priority-aware clustering and scheduling

In order to achieve scalable coordination, JRSM enables priority-aware clustering approach in which nodes that share similar synchronization schedules further grouped into clusters. Here each cluster is also assigned with a unique identifier of (C_{ID}). Here each cluster maintains intra-group synchronization via periodic broadcast messages (m_{sync}) and prevent de-synchronization and packet collision. The MAC-layer

scheduling employs dual-interval slotting. It has to be noted that packet arrivals are modeled using stochastic inter-arrival times to emulate realistic IoT traffic patterns.

- Active interval (A_I): it enables control negotiation via control packets are exchanged which are cooperative sync (p_1), RTS (p_2), CTS (p_3). These are reserve slots for different priority traffic.
- Passive interval (P_I): it enables scheduled data transfer in micro-slots with message transmission p_4 and acknowledgement (p_5).

This dual-phase design ensures collision-free and energy efficient data exchange. Here the proposed JRSM minimizes slot-allocation overhead by combining both broadcast synchronization and link-scheduling and together form a near-optimal nondeterministic polynomial (NP)-efficient approximation for two-hop collision avoidance. This strategic mechanism is also effective for medium priority traffic often ignored in the popular MAC protocols. Here the proposed framework ensures fairness between high and normal priority communications. The priority-message probability of 0.2 represents the probability of generating a priority-sensitive packet, while resulting traffic is differentiated into high, medium and normal priority classes according to the scheduling model.

Here the scheduling mechanism operates considering an energy-centric analytical model in which it considers different variables such as duty cycle ($S_{duty-cycle}$), simulation period (S_{time}), transmission period (T_{tx}), receiving period (R_{tx}), over-hearing time (T_{over}), idle hearing (T_I), passive mode time (T_{sleep}), and radio transition period (T_{radio}). Here the packet arrivals are modeled using $\delta(T_{arr})$. The traffic is also classified into three categories which are high-priority, delay sensitive packets, medium-priority, latency-tolerant packets and low priority which is background or periodic sensing data. Here each data packet p_k carries a priority tag of $P_{priority}$ and the scheduler adaptively assigns slot windows $W_c(P_{priority})$ using (5):

$$W_c(P_{priority}) = W_{min} + \Delta_w \cdot f(Q_{load}, E_{res}) \quad (5)$$

After clustering each CH allocates time slots according to priority weight and queue state (Q_{load}) and further the slot assignment matrix S_{ij} . In (5) ensures differentiated medium access while maintaining energy fairness. Here the clustering minimizes redundant contention and supports collision-free two-hop transmissions, and dynamically readjusts slots durations as per traffic inter-arrival rates. The high-priority packets are guaranteed minimal waiting time, while medium-priority traffic receives adaptive scheduling to avoid starvation. Normal traffic utilizes residual slots under low network contention. Here the adaptive slot allocation strategy assigns transmission windows dynamically based on real-time buffer state and packet priority percentage. The model also further adjusts the broadcasting energy E_{Tx}^{adj} to optimize the energy consumption. The energy model follows a standard first-order radio model for transmission and reception energy estimation. All simulation parameters and configurations are explicitly provided to ensure reproducibility of results.

Algorithm 1. JRSM joint routing and clustered MAC scheduling

Input: IoT nodes, gateway, communication range, traffic priorities

Output: Energy-aware routes and scheduled transmissions

Begin:

1. Initialize nodes, gateway, radio parameters and traffic model.
2. Construct the communication graph from node distances.
3. Calculate link costs using energy-delay routing metrics.
4. Generate energy-aware shortest paths to the gateway.
5. Classify packets into high, medium and normal priorities.
6. Form synchronized clusters and select cluster heads.
7. Allocate active control and passive transmission intervals.
8. Assign transmission slots according to priority and queue state.
9. Perform scheduled forwarding and update node energy states.
10. Repeat for the simulation period and calculate performance metrics.

End

2.5. Novelty and analytical insights

The distinctiveness of the proposed framework lies in the following aspects:

- Joint routing-scheduling integration: unlike conventional IoT approaches that optimize routing and MAC scheduling independently or via loosely coupled cross-layer designs, the proposed JRSM performs simultaneous and tightly integrated optimization, enabling efficient energy-delay trade-offs without high computational overhead.
- Priority-aware traffic handling: in contrast to existing MAC protocols such as S-MAC and Q-MAC, which primarily focus on binary or undifferentiated traffic, JRSM explicitly incorporates medium-priority traffic, ensuring balanced quality of service (QoS) across heterogeneous IoT applications.

- Low-complexity routing optimization: compared to RL-based and adaptive routing schemes, the proposed sequential graph-based evaluation with adaptive range control significantly reduces computational complexity while maintaining efficient path selection.
- Adaptive cluster-based scheduling: unlike static or contention-based scheduling mechanisms, the proposed clustering and dynamic slot allocation ensure equitable resource distribution and robust performance under high traffic intensity.

From an implementation perspective, JRSM introduces additional coordination compared with MAC-only schemes as routing and scheduling decisions are jointly considered. However, the routing component is based on graph-based shortest path evaluation rather than iterative learning, while slot allocation is performed within each cluster according to priority and queue state. Thus, the computational burden remains lower than that of learning-based routing and scheduling approaches which require repeated policy training. The clustering strategy also reduces contention and redundant control exchanges, which offer a practical trade-off between optimization performance and communication overhead. Network lifetime improvement is reflected indirectly through the higher residual energy and reduced energy dissipation reported in section 3, while scheduling efficiency is reflected by the lower packet latency achieved by JRSM.

3. RESULTS AND DISCUSSION

The performance of the proposed JRSM framework was evaluated over 500 simulation runs, and the reported results represent the corresponding average values. The same simulation configuration was used for JRSM, S-MAC, and Q-MAC to ensure consistent comparative evaluation. Here the evaluation primarily focuses on key performance indicators such as average latency, energy consumption, and residual energy under varying network sizes and message inter-arrival times.

To ensure a consistent comparison, JRSM is evaluated against S-MAC and Q-MAC as representative energy-aware MAC-layer benchmark schemes. These protocols are selected because they provide established mechanism for duty cycling, contention reduction, and energy-efficient channel access and have been widely used for evaluating MAC-layer efficiency in IoT and WSN environments [18]–[20]. Since S-MAC and Q-MAC primarily operate at the MAC layer and do not jointly optimize network-layer route selection, they provide a suitable reference for assessing the additional performance benefit obtained by integrating energy-aware routing with adaptive MAC scheduling in JRSM. Therefore, the comparison is intended to evaluate the overall network-level impact of the proposed joint design rather than to claim that S-MAC or Q-MAC provides an equivalent routing function. The routing component of JRSM is based on energy-delay-aware shortest-path selection and is therefore conceptually related to energy-aware routing approaches such as EM-RPL [8].

Table 1 shows the simulation parameters considered to evaluate the proposed JRSM along with S-MAC and Q-MAC. Figure 2 illustrates average remaining energy of IoT nodes for different message inter-arrival times that ranges between 1–10 seconds. It is evident that the proposed JRSM maintains a consistently higher residual energy compared to S-MAC and Q-MAC across all message intervals. It clearly indicates that JRSM can effectively minimize unnecessary re-transmissions and idle listening through its adaptive slot scheduling and energy-balanced routing ensuring efficient utilization of node power resources. Even under frequent short inter-arrival times JRSM sustains minimal energy degradation. Across the evaluated message inter-arrivals, JRSM maintains approximately 2% higher average residual energy than S-MAC and 2.2% higher residual energy than Q-MAC. Although the residual-energy improvement is relatively modest, it is consistent across the evaluated intervals and complements the larger reduction observed in energy dissipation, which indicate more efficient utilization of the available node energy. The higher residual energy as observed with JRSM is consistent with the energy-saving objectives reported for S-MAC-based and cluster-based scheduling approaches [18]–[20]. However, unlike these MAC-focused approaches JRSM combines scheduling with energy-aware route selection, therefore it reduces both communication contention and inefficient forwarding.

The analysis of average packet latency as highlighted in Figure 3 shows that JRSM consistently accomplishes the lowest latency across the evaluated message inter-arrival intervals. Under the evaluated traffic conditions, JRSM reduces average packet latency by approximately 26.5% in comparison with S-MAC and 19.3% compared with Q-MAC. This improvement results from the combined effect of adaptive slot allocation, which reduces contention and waiting time, and energy-aware routing which distributes forwarding activity across suitable paths. The results therefore clearly indicate that the benefit of JRSM is not limited to MAC-level contention reduction but also arises from the coordination between route selection and transmission scheduling. The latency reduction also extends the observations reported in previous TDMA and MAC-based approaches [16]–[20], where coordinated channel access was primarily used to reduce

contention and collisions. In JRSM, adaptive slot allocation is coupled with energy-delay aware routing which allows both forwarding paths and transmission opportunities to contribute to latency reduction.

Table 1. Simulation parameters

Parameters	Values
No. of IoT device	100-300
Transmission range (m)	20
Area of deployment (m ²)	1000
Radio transition time (s)	0.10 s
Channel capacity	17 kbps
Data size	18 bytes
Transmit power	$38 \times 10^{-7} \text{ J/s}$
Receive power	$18 \times 10^{-7} \text{ J/s}$
Number of simulations runs	500
Duty cycle	0.15
Probability of priority message	0.2
No. of slots	100

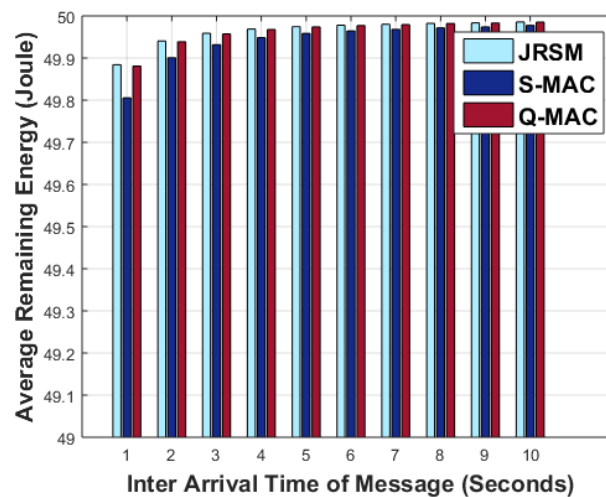


Figure 2. Analysis of average remaining energy (J)

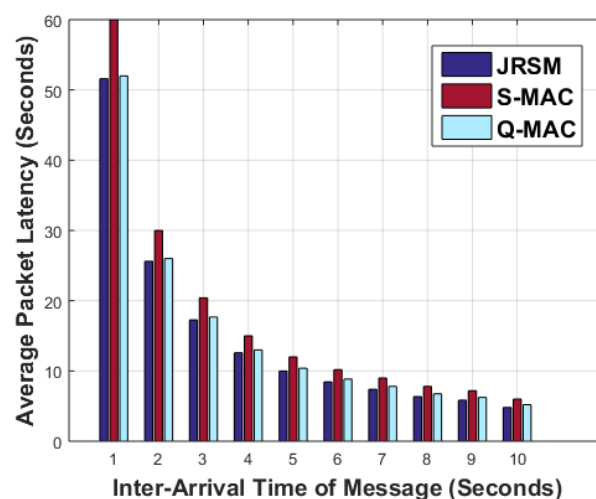


Figure 3. Analysis of average packet latency

For reproducibility, the parameters as listed in Table 1 were maintained consistently across the comparative simulations unless otherwise specified. The network size was varied from 100 to 300 nodes,

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while message inter-arrival time was also varied from 1 to 10 s to evaluate the effect of network density and traffic conditions. The duty cycle, slot count, packet size, radio transition time, transmission and reception power, channel capacity, and priority-message probability were kept fixed across the compared schemes. The routing cost function also utilizes weighting coefficients to control the relative contributions of transmission energy, residual energy condition, and delay. These coefficients were kept unchanged across all simulation scenarios, so that the performance differences arise from the routing and scheduling mechanisms rather than from scenario-specific parameter tuning. Two primary evaluation variables were considered: message inter-arrival time, varied from 1 to 10 s for latency and residual energy analysis, and network size varied from 100 to 300 nodes for energy consumption analysis. All remaining parameters were held constant according to Table 1. As the message inter-arrival time increases from 1 to 10 s corresponding to a lower packet arrival frequency, the latency characteristics of the evaluated protocols change; however, JRSM has consistently achieved the lowest latency across the evaluated intervals.

The results further confirm that JRSM efficiently handles high-frequency message arrivals with reduced contention and improved scheduling coordination and also ensure timely data delivery even under heavy IoT workloads. Figure 4 further shows that the average energy consumption per node increases with network density for all evaluated schemes. However, JRSM achieves approximately 43% lower energy dissipation than S-MAC and 4% lower energy dissipation than Q-MAC under the evaluated network conditions. The improvement is attributed to the combined effect of energy-aware link weighting, adaptive slot allocation, and cluster-based synchronization which reduces redundant transmissions and unnecessary idle listening. The larger improvement relative to S-MAC implies the benefit of combining routing optimization with coordinated MAC scheduling, while the smaller but consistent improvement over Q-MAC indicates that the joint routing component provides additional energy savings beyond MAC-level scheduling. The observed reduction in energy consumption is also consistent with the energy efficiency improvements reported by existing MAC scheduling approaches [18]–[20]. The additional improvement obtained with JRSM can be attributed to the joint consideration of routing cost and MAC scheduling which minimizes redundant forwarding, contention, and idle listening simultaneously.

The results clearly demonstrate that proposed JRSM accomplish an optimal trade-off between energy efficiency and latency, making it a scalable solution for large-scale IoT data dissemination. Slight performance degradation is observed under extremely high traffic conditions due to increased contention, although JRSM still outperforms baseline protocols. The reduction in energy consumption is attributed to minimize idle listening and balanced routing paths, which prevents energy hotspots. The observed results also reflect the inherent energy-delay trade-off achieved by JRSM.

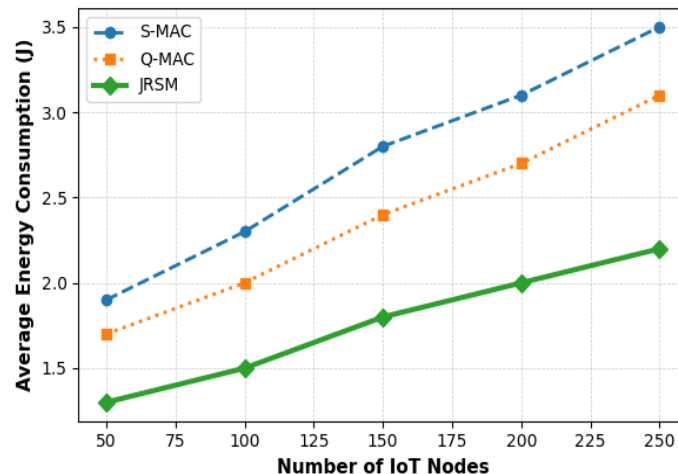


Figure 4. Average energy consumption versus number of IoT nodes, showing reduced energy usage of JRSM compared to S-MAC and Q-MAC

Table 2 highlights the methodological distinction between JRSM and representative routing, MAC scheduling and cross-layer approaches. Unlike routing only or MAC only methods JRSM jointly considers route selection and MAC scheduling while explicitly differentiating high, medium and normal-priority traffic. The quantitative performance improvements obtained by JRSM against S-MAC and Q-MAC are subsequently analyzed using residual energy, energy depletion, and packet latency. Unlike the reviewed

approaches, JRSM jointly considers routing and MAC scheduling while explicitly differentiating high-, medium-, and normal-priority traffic. Under the evaluated simulation conditions, JRSM achieves approximately 2% and 2.2% higher residual energy, 43% and 4% lower energy dissipation, and 26.5% and 19.3% lower average packet latency compared with S-MAC and Q-MAC, respectively.

Table 2. Methodological comparison of JRSM with representative routing and MAC scheduling approaches

Approach	Routing optimization	MAC scheduling	Joint routing-MAC optimization	Priority-aware traffic	Main limitation
RPL/EM-RPL [8]	✓	—	—	Limited	Routing-focused; MAC coordination not jointly optimized
RL-based routing [6]	✓	—	—	Not primary focus	Higher computational and memory requirements
TDMA-based methods [16], [17]	—	✓	—	Limited	Scheduling-focused without route optimization
S-MAC [18], [19]	—	✓	—	Limited	Mainly contention/duty-cycle management
Q-MAC [20]	—	✓	—	Limited	MAC-layer optimization without joint path selection
Cross-layer approaches [21], [22]	✓	✓	Partial	Limited	Coupling may increase implementation complexity
JRSM (proposed)	✓	✓	✓	High/medium/normal	Simulation-based validation

The current JRSM formulation primarily focuses on energy, latency, routing and MAC scheduling and does not explicitly model malicious nodes, packet forwarding attacks, denial-of-service conditions or unreliable communication links. Therefore, security and adversarial robustness are outside the present experimental scope. Future extensions will incorporate trust or security aware routing and scheduling mechanisms and evaluate JRSM under packet loss, malicious forwarding, and denial of service conditions to assess its robustness for practical IoT deployments.

4. CONCLUSION

This paper presented JRSM, a joint routing and clustered MAC scheduling framework for energy aware and delay-efficient data dissemination in IoT-based WSNs. The proposed framework thereby integrates energy-delay-aware graph-based routing with priority-aware clustering and adaptive MAC slot allocation to perform coordination among network-layer path selection and MAC-layer resource scheduling. Simulation results based on 500 runs demonstrate that JRSM achieves approximately 2% and 2.2% higher residual energy than S-MAC and Q-MAC, respectively while reducing energy dissipation by approximately 43% and 4% and average packet latency by approximately 26.5% and 19.3% respectively. These results demonstrate that jointly considering routing and scheduling can improve energy-delay performance in comparison with MAC-layer scheduling alone.

The proposed framework is particularly relevant to resource constrained IoT applications such as healthcare, industrial monitoring, precision agriculture, and smart city sensing, in which energy efficiency, timely data delivery, and scalable communication are essential. Nevertheless, the current evaluation assumes static network conditions, uniform node distribution, and network sizes up to 300 nodes.

Therefore, hardware or testbed-based validation has not yet been performed and the effects of real-radio, hardware heterogeneity, and implementation level communication overhead remain to be experimentally verified. Future work will therefore focus on hardware or testbed-based validation under dynamic and heterogeneous IoT conditions, together with the integration of reinforcement learning for adaptive routing and scheduling. Security-aware extensions and evaluation under unreliable or adversarial communication conditions will also be considered to further assess the practical robustness of JRSM.

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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

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Vi : Visualization

Su : Supervision

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Fu : Funding acquisition

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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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