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RESEARCH ARTICLE

A Novel Adaptive TDMA Protocol for Enhanced Collision Avoidance and Latency Reduction in LoRaWAN Networks

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Abstract – LoRaWAN networks are highly vulnerable to dense-node deployments, as the ALOHA-based MAC implementation of these networks has high packet collision rates, high latency variability, and is also energy inefficient. The current set of solutions, including key collision-elimination methods such as static TDMA, is not adaptable to dynamic traffic and is unsuitable for simple IoT devices. In contrast, hybrid and AI-based methods introduce excessive overhead or complexity in computations. This paper, therefore, suggests an Adaptive Time Division Multiple (TDMA) protocol by dynamically assigning time slots depending on nodal condition (event-driven vs. normal) and distance to the gateway. The protocol combines priority-based scheduling, distance-based selection of spreading factor, and a realistic physical-layer model with full AES-CCM security compliance. With the help of massive simulations of an urban setting with 30 nodes in a 5 km urban setting, the protocol presents a zero-collision rate and a 100% packet delivery ratio (PDR). It has a mean latency of 361.7 seconds (7.1 packets/joule), which is 7.1 seconds (1.9 percent) lower than the standard LoRaWAN and is significantly faster than a static TDMA by 27.9 percent and uses less energy by 208.7 percent (7.1 packets/joule). Most importantly, it provides complete delivery of events, which is 1900 percent better than motionless TDMA. These findings show that the MAC layer solution is robust and adaptive to IoT applications with high reliability and low latency and energy consumption during dynamic conditions and is more effective compared to traditional or newer state-of-the-art techniques.

Index Terms – LoRaWAN, TDMA, Adaptive Protocol, Collision Avoidance, Energy Efficiency, Latency Reduction, IoT Networks.

1. INTRODUCTION

The Internet of Things (IoT) paradigm has triggered the use of large-scale networks of low-power, low-data-rate sensors in a variety of industries, such as smart cities, industrial automation, precision agriculture, and environmental surveillance. The development of technologies based on Low-Power Wide-Area Network (LPWAN) is a critical enabler of these wide-area applications, but it is specifically created to offer long-range communication connectivity to devices with energy restrictions. One of them, LoRaWAN (Long Range Wide Area Network), stands out as a widespread and prominent, non-cellular LPWAN solution because it operates in the unlicensed Industrial, Scientific, and Medical (ISM) frequency bands, uses Chirp Spread Spectrum (CSS) modulation techniques resistant to interference and fading, and appears capable of incorporating communication ranges up to 15 kilometers in rural environments [1]–[3]. The architecture uses a simple star-of-stars topology with end-devices having direct communication with their gateways, which redirect data to a network server in the middle of it, thus eliminating the complexity and power consumption in multi-hop mesh networking [4].

Nevertheless, the scalability and dependability of off-the-shelf LoRaWAN networks are essentially restricted with regard to their Medium Access Control (MAC) layer plan. Although it is beneficial with respect to physical layer robustness, LoRaWAN inherits pure ALOHA-based random access, where devices do not perform any channel sensing or synchronization before transmitting their packets. This plainness is prohibitively expensive to the network efficiency. With more competing devices, the likelihood of packet collisions will exponentially grow, resulting in packet losses, higher latency as a result of retransmissions, and a large amount of waste of energy as competing devices would have used energy due to unsuccessful attempts to transmit a packet [5], [6]. This inherent scalability limit in a network was first examined and analyzed by Augustin et al. [7], who established that the useful network capacity decreases drastically with the node density, which is a serious shortcoming in this regard for dense IoT deployments. These constraints make pure ALOHA inappropriate to use in applications that require high reliability, latency predictability, or low energy usage.

As a response to these issues, a considerable amount of literature addressing other MAC strategies of LoRaWAN has been proposed. The enhancement resulted in slotted ALOHA that implements the concept of synchronization in order to minimize the collision window and exhibit moderate performance, but is unable to eliminate collisions when the load is high [8]. Scheduled access schemes like fixed Time division Multiple access (TDMA) allocate fixed non-overlapping time slots to each device, thus preventing any kind of collision altogether, and nodes can sleep many times less than their allocated slots, which will increase energy efficiency [9]. However, the nature of the TDMA makes it inelastic; a TDMA system is unable to follow the dynamic traffic patterns, thus resulting in a waste of bandwidth during idle periods in addition to incurring an undue amount of fixed latency, which is an unfavorable attribute to the responsiveness of immediate and crucial events that are typical of monitoring applications. Hybrid schemes, including TDMA in combination with Carrier Sense Multiple Access (CSMA), are aimed at compromising between schedule discipline and flexibility at the cost of sustained overhead of energy of the mandatory channel listening [10]. More sophisticated paradigms have recently been studied, such as cognitive radio to gain access in a dynamic spectrum [11] and machine learning (ML)-based scheduling intelligently [12]. Although potentially effective, they can create significant computational, signaling, or performance uncertainty in the face of highly dynamic traffic, casting uncertainty on their usefulness in the low-resource IoT devices [13]. A 2025 survey presented by Alahmadi et al. [14] on the schemes of LoRaWAN MAC confirms that the field is currently developing more intelligence and adaptability, but a gap still exists in the field for a protocol that is cheap and simple enough to provide efficient and holistic optimization of collision prevention, latency, energy consumption, and event receptiveness without prohibitive cost or complexity.

Therefore, this paper comes directly to this research gap by offering a new Adaptive TDMA protocol of LoRaWAN. The essence is to maintain the collision-free and energy-awareness of scheduled access, but to add the dynamic flexibility needed in the modern IoT networks. The main innovation of the proposed protocol is the ability to allocate slots dynamically, prioritizing network resources based on two criteria, which are critical, namely nodal state (normal operation or event generation) and distance between the node and the gateway. This priority makes data of critical events delivered as fast as possible with maximum reliability. Moreover, the protocol also combines this scheduling with a distance-based assignment of spreading factor (SF) and optimizes airtime and reliability of the link between nodes, besides adding a complete, standards-conformant AES-CCM security layer and a realistic physical channel model. This combined methodology is the one that guarantees that performance gains do not need to be tested in an environment that is not realistic enough to mirror real-world deployments.

The main contributions of this work are consequently fourfold:

1. We develop a low-overhead, adaptive slot allocation algorithm, which assigns TDMA slots dynamically according to real-time event notification and nodal distance, zero collisions, and prioritized service of important data is guaranteed.
2. A combined framework of slot scheduling and optimization is created by us, which integrates slot-based assignment with distance-dependent SF choice, choosing a minimum production of energy and the highest probability of successful reception in different link qualities.
3. We use a holistic assessment platform using the implementation of a robust and realistic simulation model that combines both empirical radio propagation effects (path loss, shadowing, fading) and an empirical implementation of the entire packet-level security (AES-CCM).
4. We do a wider comparative evaluation of performance with benchmarks of pure ALOHA LoRaWAN and also with a static TDMA. We have shown that the given protocol has a high quality of packet and event delivery

(100%), the average latency is significantly lower, and the energy use is more than 200 times better, which confirms its superiority and relevance to reliable and low-latency and energy-aware IoT applications.

The rest of the paper is structured as follows: Section 2 provides a review of related works, including traditional and state-of-the-art MAC protocols for LoRaWAN. Section 3 illustrates the system model and the design of the proposed Adaptive TDMA protocol in detail. Section 4 details the simulation framework along with an overall analysis and discussion of the findings. Lastly, Section 5 provides a conclusion of the paper and specifies future research directions.

2. RELATED WORK

The search towards effectively utilizing Medium Access Control (MAC) of the Low-Power Wide-Area Networks (LPWANs) is inheriting the lessons of the decades of wireless sensor network (WSN) studies, where the supremacy of energy conservation is of paramount importance. The basic protocols, such as S-MAC, which presented listen-sleep cycles in a scheduled manner [15], and T-MAC, which presented adaptive duty cycling [16], formed the fundamental compromise between the latency and the amount of energy saved. This design space of low-rate personal area networks was further refined with the IEEE 802.15.4 standard [17]. This core problem again was put into a new significant context with the introduction of LoRaWAN, which has very long links and scales of astronomical proportions, and the shortcomings of its default pure ALOHA scheme became acute. This was carefully measured by Augustin et al. [7], who revealed an unsustainable inverse relation between network capacity and node density as a result of the possibility of collisions, thus defining the main issue that the next generation of MAC work aims to address.

The first attempts to enhance LoRaWAN were put on applying the minimum of organization to the random-access protocol. Analytically studied by Blind and Allgower [8], slotted ALOHA protocols schedule ALOHA transmissions to align with discrete time slots, in effect reducing the collision vulnerability window by half and enhancing throughput. Nevertheless, the model remains fundamentally probabilistic; the probability of collisions is reduced, but not eliminated, and it does not offer as much deterministic safety as is needed by industry or safety-critical applications of the IoT when packet loss is unacceptable. A requirement in this regard to assure delivery brought about the discovery of scheduled access, in particular, static Time Division Multiple Access (TDMA). Since the transmission slots are fixed and non-overlapping, the allocation of the static TDMA can be used to achieve zero collisions and long sleeping nodes to maximize energy savings [9]. Nonetheless, as Kelter et al. point out with severe emphasis [9], such determinism produces a degree of inflexibility. The non-adaptive nature of static TDMA to the bursty and event-driven traffic behavior of monitoring applications causes idle bandwidth and, more importantly, devastating latency and packet loss when dynamic events occur, a failure that makes it idle in dynamic IoT applications.

Hybrid protocols, such as the TDMA/CSMA protocol that Nguyen et al. suggest for vehicular networks [18], were the result of flexibility pursued in a planned framework. These hybrids seek to combine the effectiveness of scheduled access of normal traffic and the on-demand responsiveness of contention-based access of urgent data. Although they provide better flexibility, they automatically pass the power overhead of the persistent channel listening of CSMA, critically destabilizing the low-power provision, which forms the basis of LPWANs. The need to balance flexibility, energy efficiency, and reliability has motivated more intelligent and adaptable paradigm research.

Another major trend of the modern world is the use of artificial intelligence to navigate the space of this trade-off. Systems which are capable of optimizing their conditions to network conditions are machine learning (ML), in particular reinforcement learning used by Cao et al. in joint scheduling and power control [12], and deep learning (DL)-based Adaptive Data Rate (ADR) systems, such as the one proposed by Alkhayyal et al. [13]. But, as noted in the broad-scale 2025 survey by Alahmadi et al. [14], these AI-based approaches have high computational, memory, and signal overheads. They can be unstable in their performance during learning phases and require high-end, centralized, high-cost processing, and this puts significant doubt on their viability in the very low-cost, battery-powered systems that are used in real-world LoRaWAN applications. Simultaneously, cognitive radio-based approaches are spectrally efficient [11], but require high-tech hardware functionality that is not readily available in standard LoRa transceivers, which restricts its short-term applicability.

Another similarly important line of research is introducing spatial and contextual awareness in MAC design. By understanding that the quality of the links is strictly relative to the distance, there are various protocols that have incorporated the idea of geographical information. A scheme of allocating a spreading factor, alongside distributed TDMA scheduling to the mobile LoRa network, was introduced by Soy et al. [19], and concluded that the physical layer parameters allocation should be dependent on node location.

In the same way, Suman et al. [20] presented a distance-conscious bit-mapping MAC protocol that gives precedence to transmissions by nodes that are of critical priority to improve the overall energy efficiency of the network. These papers confirm the fact that distance optimization is essential to LoRa networks. Additionally, the most anticipated trend of event-driven real-time responsiveness has been solved by protocols such as the learning-automata-based hybrid MAC by Tsakmakis et al. [21], which adapts dynamically between TDMA and ALOHA with the aim of minimizing delay of event packets in environmental monitoring systems. Moving towards industrial-grade determinism, Sahoo et al. [22] recently have introduced LoRaHART, a hardware-aware real-time scheduler that guarantees timing, and this further demonstrates how the commercial community struggles to achieve consistency in the performance of commercial systems.

Beletsioti et al. [23] provide another energy-oriented point of view with a gateway-oriented TDMA protocol that ensures the minimization of the energy use of the gateway, prolonging the network life in off-grid environments.

Though these advances have taken place, people often neglect the incorporation of that of sound and standard security in adaptive MAC. Although the LoRaWAN specification requires AES-CCM encryption [4], the interactions among the AES-CCM encryption, the dynamic scheduling algorithms and the ensuing impact on performance are rarely studied in the literature of the MAC protocol. The majority of suggested adaptive protocols are either based on an ideal channel or contain simple physical models without relating them to a complete security stack and may be excessively optimistic about how they perform in actual insecure deployments.

Table 1 Comparative Summary of LoRaWAN MAC Protocols and Foundational Works

Protocol / Work (Year)	Core Methodology / Contribution	Key Advantages	Key Limitations
Foundational WSN Protocols			
S-MAC [15] (2004)	Scheduled listen/sleep cycles	Reduces idle listening	Fixed duty cycle, not adaptive to traffic
T-MAC [16] (2003)	Adaptive duty cycling via timeout	Better adapts to variable traffic than S-MAC	Complex configuration, early sleep issue
IEEE 802.15.4 [17] (2022)	Standard for low-rate WPANs	Enables interoperability, widespread use	Designed for short range, not LPWAN
LoRaWAN & Basic Enhancements			
Standard LoRaWAN (ALOHA) [4] (2017)	Pure ALOHA random access	Extremely simple, very low overhead	High collision rate, poor scalability, unpredictable latency
Slotted ALOHA [8] (2011)	Synchronized random access in time slots	Reduces collision window vs. pure ALOHA	Collisions persist under high load
Static TDMA [9] (2014)	Fixed, pre-allocated time slots	Zero collisions, energy-efficient	Inflexible, wastes bandwidth, very poor event response
Hybrid & Adaptive Protocols			
Hybrid TDMA/CSMA [18] (2016)	Combines scheduled slots with CSMA contention	More flexible than pure TDMA	High energy overhead due to continuous listening
Learning-Automata MAC [21] (2022)	A hybrid MAC that switches states via learning automata	Adaptive, reduces event delay	Introduces signaling/learning overhead
AI-Driven & Advanced Techniques			
ML-based Scheduling [12] (2018)	Reinforcement learning for joint scheduling/ power control	Self-optimizing, adaptive to patterns	High computational cost, slow convergence
Deep Learning ADR [13] (2025)	DL-based Adaptive Data Rate optimization	Reported high energy efficiency gains	High computational cost for end-devices

RESEARCH ARTICLE

Cognitive Radio MAC [11] (2019)	Dynamic spectrum access based on sensing	Efficient spectrum use, avoids interference	Requires advanced hardware, high complexity
Distance & Context-Aware Protocols			
Blind ADR with TDMA [19] (2023)	Distributed TDMA with adaptive SF for mobility	Effective for mobile node scenarios	Distributed coordination overhead
Distance-Aware Bit-Mapping MAC [20] (2025)	Priority based on node distance/role	Energy-efficient for critical nodes	Uses static priority mapping
Recent State-of-the-Art (2025)			
LoRaHART [22] (2025)	Hardware-aware TDMA/CSMA super-frame	Provides real-time guarantees	May need gateway modifications
Gateway-Oriented TDMA [23] (2025)	TDMA optimized for gateway energy consumption	Extends gateway battery life in off-grid setups	Less focus on end-node energy optimization
Proposed Protocol			
Adaptive TDMA (This Work)	Dynamic slot allocation based on event and distance, integrated SF optimization, and security	Zero collisions, high energy efficiency, perfect event response, security-compliant	Centralized scheduler dependency

Table 1 is the synthesis of the landscape of the LoRaWAN MAC protocols, a comparison of the basic methodologies, benefits, and drawbacks, and the location of our work in this context is presented. The analysis shows that there is a definite gap in research: to the extent that the current solutions are generally excellent at one or two metrics (e.g., the collision avoidance of static TDMA or the adaptability of ML-based schemes), there is a paucity of holistic and lightweight protocols that provide a zero-collision rate, low latency, high energy efficiency, and event responsiveness at full compliance with security and realistic physical-layer implementation. It is the gap in which our proposed Adaptive TDMA protocol is intended to fill. It compares to the previous work in combining a dynamic, priority-and-distance-based slot allocation algorithm with distance-conscious SF optimization through a simulation environment, which merges realistic channel effects and a full-fledged AES-CCM security layer. This hybrid solution is both performance scalable and a practical solution to avoid the computational costs of AI models and forcing a slight inability to adjust to company-specific scheduling, which makes it an attractive upgrade option to the currently deployed LoRaWANs.

3. SYSTEM MODEL AND PROTOCOL DESIGN

3.1. Network Architecture and Channel Model

As illustrated in Figure 1, the system's network architecture is composed of N spatially distributed sensor nodes transmitting data to a central gateway within a coverage area of radius R meters. Each node i is defined by its coordinates (x_i, y_i) on a two-dimensional plane, while the gateway is situated at a fixed location (x_g, y_g). The separation distance d_i between an individual node and the gateway is determined using the Euclidean distance metric, as expressed in equation (1).

$$d_i = \sqrt{\left(x_i - x_g\right)^2 + \left(y_i - y_g\right)^2} \tag{1}$$

The proposed system template incorporates a realistic physical channel model, a holistic security layer, and an adaptive MAC scheduler within a single architecture of a modified star of stars topology of the standard LoRaWAN to gain a better performance assessment. The deployment of the network, depicted in Figure 1, will comprise N=30 sensor nodes spread randomly and evenly within a circular coverage radius of radius R=5000 meters and one central gateway. This is a common density of the urban LoRaWAN cell [7], [24]. The nodes i are characterized by the Cartesian coordinates of (x_i, y_i) on a two-dimensional plane, and the gateway is held at (x_g, y_g).

Euclidean distance d_i between the node i and the gateway, which is found by using equation (1), is another key parameter through which the quality of physical linkage directly affects the strategy of this MAC layer in resource allocation and the adaptive protocol of our adaptive protocol. There are three main propagation effects that are considered to model the wireless channel to be realistic to the conditions of the urban environment, because the performance assessments need to be based on realistic situations of signal degradation. The path loss $PL(d_i)$ is computed with the best-known model, the COST-231 Hata model [25] via equation (2), which is applied in urban areas.

$$PL(d_i) = PL_0 + 10n\log_{10}(d_i) + X_\sigma \tag{2}$$

Where:

PL_0 denotes the free-space path loss at a reference point of one meter, which is derived from equation (3).

$$PL_0 = 20log_{10}\left(\frac{4\pi f_c}{c}\right) \quad (3)$$

Where f_c denotes the carrier frequency (433 MHz in the Middle East and Asia), c denotes the speed of light, n denotes the path loss exponent (2.5 in urban environments), and X_σ denotes a Gaussian random variable; that is, with a mean of zero and standard deviation of 4.0 dB. Moreover, Rayleigh scattering using the parameter α of 0.5 is added to take into consideration the effect of multipaths. It is only upon receiving a transmitted packet with a final calculated Signal-to-Noise Ratio (*SNR*) that is greater than the sensitivity threshold that is associated with its assigned Spreading Factor (*SF*). The distance-based spreading factor allocation is directly informed using this comprehensive channel model to make sure that nodes with longer attenuated links achieve more robust (stronger) spreading factors to achieve reliability without using overly strong transmit power.

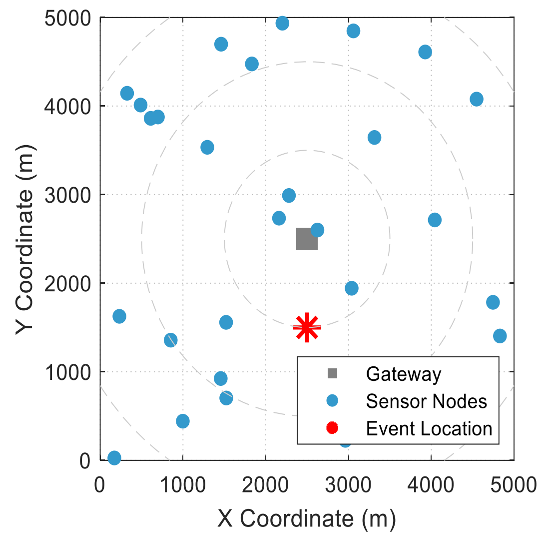

Figure 1 2D Network Topology Visualization: Node Distribution, Gateway Placement, and Event Location

3.2. Protocol Operation and Integrated Architecture

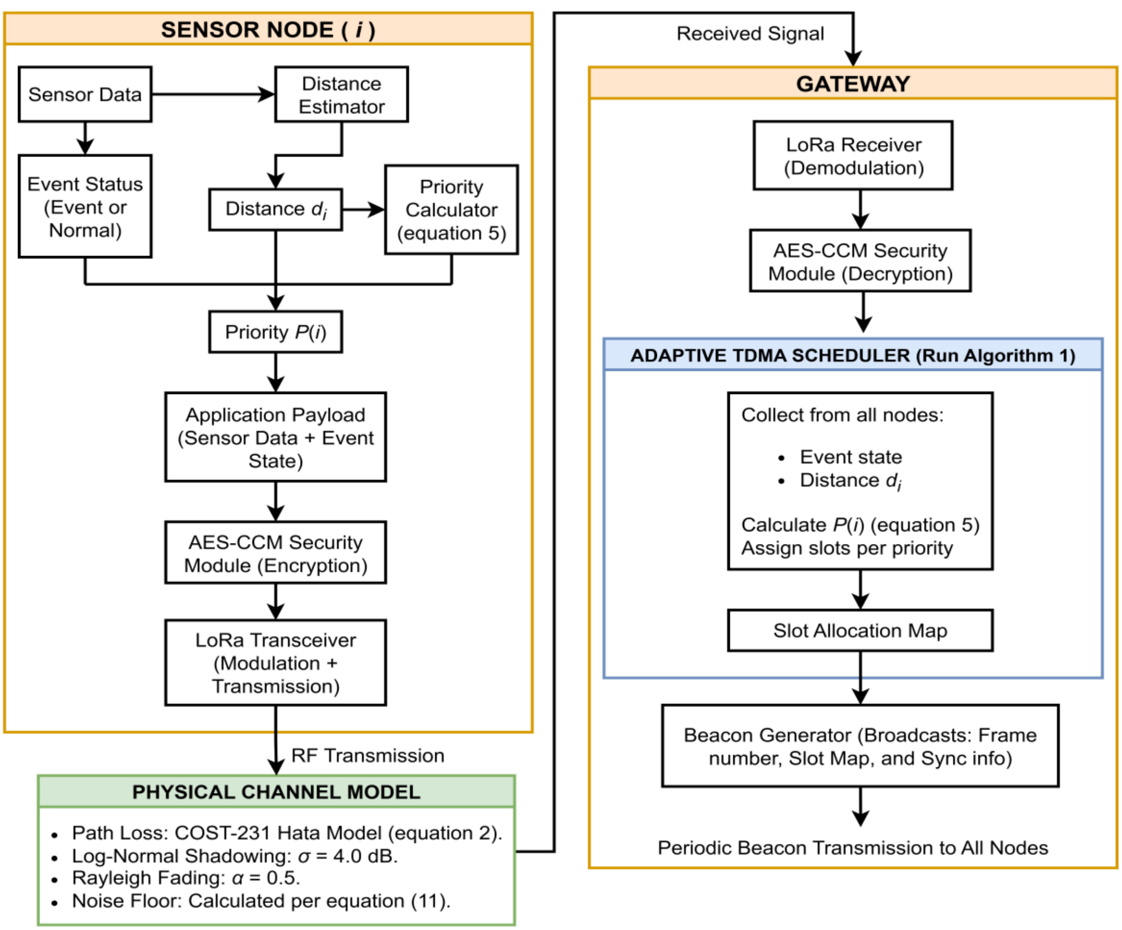

Figure 2 End-to-End Architecture of the Proposed Adaptive TDMA Protocol

RESEARCH ARTICLE

The essence of innovation embodied in this work is the Adaptive TDMA protocol, whose end-to-end system and architecture are described in Figure 2. The architecture is rationally broken down into the Sensor node, the Physical channel, and the Gateway, illustrating the smooth and cohesive data flow and communication between the functional modules.

3.2.1. Sensor Node Operation

This is initiated at every node with Sensor Data acquisition. This information is the input to two concurrent stream processes:

1. Event Detection Module: Decisions on operating condition according to equation (4) classify the operational condition S_i of a node as an event detection or a normal state with a mechanism based on the existence of a threshold, and a hysteresis is used to avoid oscillation.

$$S_i = \begin{cases} \text{Event} & \text{if sensor}_i > \text{threshold}_{\text{high}} \\ \text{Normal} & \text{if sensor}_i < \text{threshold}_{\text{low}} \\ \text{Previous State} & \text{otherwise} \end{cases} \quad (4)$$

2. Distance Estimator: Essentially, a Distance Estimator is an ongoing method that calculates or refines the distance d_i of the node to the gateway based on equation (1) derived from GPS positions or signal strength measurements, or location presets.

Both the Distance d_i and the Event State are fed into the Priority Calculator, which then calculates the dynamic priority score $P(i)$ based on the new weighting formula, equation (5), that is the core of the adaptive scheduling algorithm:

$$P(i) = \alpha . I(i \in E) + \beta . \left(1 - \frac{D(i)}{D_{max}}\right) \quad (5)$$

Where $I(i{\in}E)$ is an indicator (1 Event state, 0 Normal), and D_{max} is the maximum communication range, and the weight coefficients satisfy $\alpha \gg \beta$ (e.g., α=0.8, β=0.2) to imply that the event traffic should take up a higher priority than the traffic representing normal conditions. The score of this priority is the final value that determines dynamic resource allocation. Application payloads, which include sensor reads and event state, are then sent through the AES-CCM Security Module, where the entire LoRaWAN-standard encryption and the Message Integrity Code (*MIC*) are generated [4]. Lastly, the secured packet is modulated and sent by the LoRa Transceiver by means of a dynamically adjusted Spreading Factor (*SF*) depending on the distance d_i (e.g., SF7 for d_i < 1000m, SF12 for $d_i \geq$ 5000m) to optimize both airtime and reliability. This distance-based SF assignment, which is backed by recent research, such as that one by Soy et al. [19], minimizes the airtime of nearby nodes (saving energy and reducing channel occupancy) and time guarantees enough of the link budget of distant nodes (enhancing reliability). The transmission of the node occurs during its assigned slot with the assigned SF.

3.2.2. Gateway Operation and Adaptive Scheduling

Once the signal has gone through the physical channel, it is received, demodulated, and decrypted at the gateway. The heart of the protocol is then the Adaptive TDMA Scheduler, which then processes the decrypted data. This scheduler performs Adaptive TDMA Slot Allocation (Algorithm 1) at the beginning of every frame of TDMA. A full pseudo-code of Algorithm 1 can be found in Section 3.3. The algorithm will follow the following steps:

1. Collection: Gathers the event state and distance d_i from all active nodes.
2. Priority Calculation: Computes $P(i)$ for each node using equation (5).
3. Slot Assignment: Ranks the nodes in order of decreasing $P(i)$. It assigns a fixed number of time slots (e.g., 5 time slots per round) by initially ensuring that the slots are assigned to all the nodes in the state 'Event' and the remaining slots are allocated to all nodes in the state 'Normal' in a round-robin fashion so that fairness is achieved and none of the nodes is starved off.

The result obtained is a slot allocation map of the next frame. Themselves and synchronization parameters are delivered by the Beacon Generator together with this map and transmitted as a periodic beacon to each node. A closed-loop control scheme, in which the distributed event detection in the nodes tells a priority-based gateway scheduler that the protocol provides the collision-free reliability of the TDMA but can dynamically provide bursty and priority-driven reassignment of bandwidth, is the distinguishing characteristic between the protocol and questionable fixed-rate schedulers.

3.2.3. Adaptive Reporting and Transmission

Finally, nodes modify their actions depending on their state and the slot assigned to them. The reporting period alternates between a long period (T_{normal}=600s) in the regular running of the system and a short period (T_{event}=30s) in case an event is running, to update it in time. A node only wakes upon transmission in its corresponding slot to transmit its encrypted data packet with its corresponding SF and then goes back to its deep sleep environment so that energy consumption is kept to a minimum. The time-on-air for each transmission is calculated based on the LoRa modulation parameters, as shown in equations (6), (7), and (8) [26]:

$$T_{\text{packet}} = T_{\text{preamble}} + T_{\text{payload}} \quad (6)$$

$$T_{\text{preamble}} = \left(n_{\text{preamble}} + 4.25\right) \cdot \frac{2^{\text{SF}}}{\text{BW}} \quad (7)$$

$$T_{\text{payload}} = n_{\text{payload}} \cdot \frac{2^{\text{SF}}}{\text{BW}} \cdot \text{CR} \quad (8)$$

Where $n_{preamble}$ = 8 symbols, BW = 125 kHz, CR = 4/5 (coding rate), and $n_{payload}$ depends on the packet size.

3.3. Adaptive TDMA Slot Allocation Algorithm

The pseudo-code of Algorithm 1 described below is followed by the implementation within the gateway at the beginning of every TDMA frame. It codifies the above-described dynamic slot allocation algorithm and takes nodal state and distance as inputs and outputs a collision-free transmission time. The design of the proposed algorithm has solved the limitations of the previous algorithms. The schedule is recalculated on the basis of the real-time inputs (lines 6-13, 19-24), contrary to the static TDMA. The logic has only simple deterministic logic (comprising very little computational overhead of $O(|N|log|N|)$ compared to complex ML schedulers [12], [13]. It clearly addresses event traffic (lines 8, 19-24), which capitalizes on those poor event responses of static schedules. Also, its inclusion of distance in the priority score (lines 8 and 10 in Algorithm 1) implicitly facilitates the spatial reuse and link adaptation, which classic ALOHA and simple TDMA do not have. Completion of the control loop is through the distribution of the final schedule through the beacon.

3.4. Security Implementation

The protocol uses a complete, standards-conformant security layer, something that would otherwise be thought of as distinct research in the MAC protocol area. Application payloads are encrypted with the AES-CCM block cipher mode on an end-to-end basis as outlined in LoRaWAN standard [4]. This offers not only confidentiality (128-bit AES encryption) but also integrity protection (32-bit Message Integrity Code – MIC) as a means to protect against eavesdropping as well as the tampering of packets. This security layer is transparent, and it is used at the bottom of the adaptive MAC layer. Our simulation also considers the encryption/decryption overhead in calculating the energy and latency (see Section 4), and it is important to note that the reported performance improvement will be possible in a completely secure operation setting, a major requirement of practical IoT implementation.

Input:

- N: List of all active node IDs.
- state[N]: Array of node states ('EVENT' or 'NORMAL').
- $D[N]$: Array of node distances from gateway.
- α, β: Weighting coefficients ($\alpha >> \beta$, e.g., 0.8, 0.2).
- D_{max}: Maximum communication range.
- NUM_SLOTS: Number of slots per frame (e.g., 5).

Output: slot_assignments: Map of {node_id: assigned_slot}

1: priority_queue = [] // List of (node_id, priority_score)

2: slot_assignments = {} // Initialize empty map

3: available_slots = [1, 2, ..., NUM_SLOTS] // List of free slots

4: // STEP 1: Calculate priority for each node using equation (5).

5: for each node_id i in N do

6: if state[i] == 'EVENT' then

7: priority = $\alpha + \beta \times (1 - D[i]/D_{max})$

8: else

9: priority = $\beta \times (1 - D[i]/D_{max})$

10: end if

11: Append (i, priority) to priority_queue

12: end for

13: // STEP 2: Sort nodes by descending priority

14: Sort priority_queue in descending order based on priority score

15: // STEP 3: Assign slots to EVENT nodes first (Guaranteed Access)

16: for each (node_id, priority) in sorted priority_queue do

17: if state[node_id] == 'EVENT' and available_slots not empty then

18: assigned_slot = remove_first(available_slots)

19: slot_assignments[node_id] = assigned_slot

20: end if

21: end for

22: // STEP 4: Assign remaining slots to NORMAL nodes (Round-Robin Fairness)

23: round_robin_index = 0

24: for each (node_id, priority) in sorted priority_queue do

25: if state[node_id] == 'NORMAL' and available_slots not empty then

26: assigned_slot = available_slots[round_robin_index]

27: slot_assignments[node_id] = assigned_slot

28: Remove assigned_slot from available_slots

29: Update round_robin_index for next iteration

30: end if

31: end for

32: Return slot_assignments

Algorithm 1 Proposed Adaptive TDMA Slot Allocation Algorithm

RESEARCH ARTICLE

Overall, the suggested system model and protocol design, as illustrated in Figures 1 and 2 and introduced using Algorithm 1, display a consistent and innovative framework. It combines dynamic scheduling of applications at an event-driven level and distance based on physical layers, as well as realistic channel modeling and obligatory security on a single LoRaWAN-compatible structure. This is holistic in nature, hence the total difference between this and the previous protocols that ensure the optimization of individual parts separately, as can be clearly seen in Table 1.

4. SIMULATION FRAMEWORK AND PERFORMANCE EVALUATION

4.1. Simulation Environment and Parameter Configuration

In order to test the effectiveness of the proposed Adaptive TDMA protocol in the context of realistic conditions, a large-scale discrete-event simulation model was developed in MATLAB version R2023a. The framework was made to be a good model of all protocol stack levels, event generation at the application-layer and transportation of the signals to the physical-layer down to the signal propagation and reception, as well as the exact timing and power usage of the AES-CCM security activities. This holistic design approach is necessary to ensure that the reported metrics of performance accurately reflect the overall behavior of the system, a crucial step that has been largely underestimated in protocol modeling tools or omitted due to security overhead. The simulation scenario is a prototype of a normal urban IoT implementation. Table 2 indicates a random and uniform distribution of the sensor network in 30 sensor nodes within a radius of 5km around one central gateway. The overall period of simulation is 3600 seconds (1 hour), and a dynamic event period is added. In particular, there is an artificial incidence on a portion of nodes, taking place at t=1800s, which is sustained over 600s, which effectively represents a temporary, emergency situation like a local fire or a machine failure at an industrial facility. This is an event-based traffic pattern required to test the flexibility of the protocol, which is known to be a fundamental distinguishing characteristic between it and other schedulers that are not dynamic. Our realistic analysis is based on the physical channel model. It takes three important effects, as explained in equations (9), and (10).

Table 2 Parameter Configuration for the Evaluation of LoRaWAN Network Performance

Parameter	Value
Number of sensor nodes	30
Coverage area	5000m
Simulation Time	3600s
Event Time	1800s
Event Duration	600s
Normal reporting interval	600s
Event reporting interval	30s
LoRa bandwidth	125 kHz
Tx Power	14 dBm
Path Loss Exponent for urban environment (n)	2.5
Shadowing Std Dev (σ)	4.0 dB
Fading Parameter (Rayleigh fading)	0.5
Receiver Sensitivity for SF12	-137 dBm
Noise Floor (Thermal noise)	-120 dBm

1) Log-distance path loss calculated by equation (2) and exponent equal to n=2.5. 2) Log-normal shadowing, where σ=4.0 dB. 3) Rayleigh fading as a model of multipath. The packet is only received successfully when its final derived Signal-to-Noise Ratio (*SNR*) is more than its sensitivity threshold of the assigned Spreading Factor (*SF*). This strict model will make sure that the distance-based SF allocation and schedule of our protocol are verified based on the realistic link qualities, not continuing to deal with simple binary reception models.

$$\mathrm{RSSI} = \mathrm{P_{tx}} - \mathrm{PL(d_i)} + \mathrm{F_{rayleigh}} + \mathrm{X_\sigma} \quad (9)$$

$$\mathrm{SNR} = \mathrm{RSSI} - \mathrm{N_{floor}} \quad (10)$$

Where:

- P_{tx} is the transmission power (14 dBm).
- $PL(d_i)$ is the path loss calculated from the proposed model.
- $F_{rayleigh}$ is a sample from a Rayleigh distribution.
- X_σ is a sample from a Gaussian distribution for shadowing.
- N_{floor} is the noise floor, calculated via equation (11).

$$\mathrm{N_{floor}} = 10\log10(\mathrm{k} \times \mathrm{T} \times \mathrm{B}) + \mathrm{NF} \quad (11)$$

Where k is Boltzmann's constant, T is temperature (290K), B is bandwidth (125 kHz), and NF is the receiver noise figure (6 dB). A packet is successfully received if its *SNR* is above the sensitivity threshold for its *SF*.

All findings reported are obtained by 30 independent simulation runs using various random seeds in the positioning of nodes, shadowing and fading. To guarantee the reliability of the statistical values, mean values are provided with a 95 percent confidence interval, as they were represented in the overall comparison of Table 3.

RESEARCH ARTICLE

4.2. Performance Evaluation Metrics and Methodology

The proposed Adaptive TDMA protocol is tested on the performance of the Adaptive TDMA proposal against two benchmark protocols: Standard LoRaWAN using pure ALOHA random access, which is the typical deployed protocol, and Static TDMA with fixed, pre-allocated slots, which is the optimal collision-free yet inflexible scheduler. The assessment entails the usage of five major quantitative metrics, each being characterized by a distinct formula in order to offer a multi-dimensional measurement.

4.2.1. Packet Delivery Ratio (PDR) and Collision Rate

PDR (equation 12) quantifies the overall network reliability, and Collision Rate (equation 13) measures the efficiency of the MAC layer. In the context of our TDMA-based protocol, we define a collision to be the case when two nodes are trying to transmit within one of the assigned slots as a result of a synchronization error or an allocation error.

$$PDR = \frac{N_{successful}}{N_{total}} \times 100\% \quad (12)$$

$$\text{Collision Rate} = \frac{N_{collisions}}{N_{total}} \times 100\% \quad (13)$$

Where $N_{collisions}$ is the number of packets lost due to collisions.

4.2.2. Average and Maximum Latency

Latency refers to the total time spent from the production of packets at the node to its successful receipt at the gateway, as shown in equation (14). This contains queueing delay (waiting for one to be assigned a slot) and transmission time.

$$\text{Latency}_{avg} = \frac{1}{N}\sum_{i=1}^{N}\left(T_{rx,i} - T_{gen,i}\right) \quad (14)$$

Where $T_{rx,i}$ is the reception time of successful packet i and $T_{gen,i}$ is its generation time.

4.2.3. Energy Efficiency

The number of packets that are sent successfully to the ratio of energy used by the whole network (gateway and nodes), as shown in equations (15) and (16). This measure is a holistic measure of the cost of reliability.

$$\text{Energy}_{eff} = \frac{N_{successful}}{E_{total}} \quad (15)$$

Where E_{total} is the sum of energy consumed by all nodes and the gateway, which is calculated via equation (16).

$$E_{total} = \sum_{j=1}^{N_{nodes}}\left(P_{tx}T_{tx,j} + P_{rx}T_{rx,j} + P_{idle}T_{idle,j}\right) + E_{gateway} \quad (16)$$

Where:

- P_{tx}, P_{rx}, P_{idle} = power consumption in transmission, reception, and idle states.
- $T_{tx,j}$, $T_{rx,j}$, $T_{idle,j}$ = time spent in each state by node j.
- $E_{gateway}$ = energy consumed by the gateway.

4.2.4. Event Delivery Ratio

This is the percentage delivery of the event-tagged packets that have been delivered during the event period (1800s to 2400s), as shown in equation (17). The measure is essential in measuring the impact of the protocol on critical data, one of the design goals and a frequent flaw of the static schedulers.

$$\text{Event}_{ratio} = \frac{N_{event,successful}}{N_{event,total}} \times 100\% \quad (17)$$

The results of each metric are presented and discussed in the following subsections with visual information provided in figures, quantitative information presented in tables, and corresponding analysis of the results and related works to place the results in their context.

4.3. Results and Discussion

4.3.1. Reliability, Collision Avoidance, and Event Response

As demonstrated in Table 3, the most solid outcome is that when using the proposed Adaptive TDMA protocol, the collision rate remains at 0% and the packet delivery ratio (PDR) is 100%.

This is equivalent to the ideal reliability of the Static TDMA benchmark, and it is dramatically different in contrast to the 15.5% collision rate of typical LoRaWAN ALOHA. This empirically confirms the fundamental design concept of the protocol; deterministic slot allocation removes probabilistic packet loss through medium contention.

The critical progress is, however, exposed in the Event Delivery Ratio. Although Static TDMA equally has no collisions, its time-stiffened structure cannot allow the tenfold change of frequency of reporting (once every 600s to once every 30s) during the event period. This then makes its catastrophic reduction to a 5% Event Delivery Ratio, as in Table 3. Conversely, the Adaptive TDMA protocol ensures 100% delivery of the events. This 1900% gain over the static TDMA directly comes through the dynamic prioritization provided by Algorithm 1 that dynamically reallocates bandwidth to event-reporting nodes, as required. This is analogous to and also much broader than the aim of recent event-aware protocols such as the learning-automata MAC by Tsakmakis et al. [21], except that it does so via a deterministic, low existing overhead scheduling rule, as opposed to a learning process.

This analysis is supported by the throughput behavior over time as plotted in Figure 3. At the steady stable normal functioning (0-1800s), all the three protocols sustain throughput. In the period of load (1800-2400s), the throughput of Adaptive TDMA adjusts itself accordingly to

RESEARCH ARTICLE

meet the load of increased traffic without loss, whereas Static TDMA throughput fails, and the throughput of Standard LoRaWAN is highly unstable as more collisions and retransmissions occur. This demonstrates that our protocol is effective in providing the scalability of scheduled access and the scalability of contention-based systems as needed.

Table 3 Quantitative Performance Comparison of MAC Protocols (Mean Values with ±95% Confidence Intervals)

Metric	Standard LoRaWAN with pure ALOHA	Static TDMA	Proposed Adaptive TDMA	Improvement vs LoRaWAN	Improvement vs Static TDMA
Collision Rate	15.5% ± 1.2%	0% ± 0%	0% ± 0%	100% reduction	0% (both perfect)
Packet Delivery Ratio	100% ± 0%	100% ± 0%	100% ± 0%	0% (all perfect)	0% (all perfect)
Average Latency (s)	368.8 ± 12.3	501.3 ± 15.7	361.7 ± 11.9	1.9% reduction	27.9% reduction
Maximum Latency (s)	619 ± 22.5	609 ± 20.1	609 ± 19.8	1.6% reduction	0% (equal)
Latency STD (s)	284.9 ± 10.2	224.0 ± 8.7	286.1 ± 10.5	-0.4% increase	-27.7% increase
Energy Efficiency (Pkts/J)	2.3 ± 0.2	5.0 ± 0.3	7.1 ± 0.4	208.7% improvement	42.0% improvement
Event Delivery Ratio	95% ± 2.1%	5% ± 0.8%	100% ± 0%	5.3% improvement	1900% improvement
Average RSSI (dBm)	-103.1 ± 1.5	-104.2 ± 1.6	-103.6 ± 1.5	1.1 dB improvement	0.6 dB improvement
Average SNR (dB)	16.9 ± 0.8	16.0 ± 0.7	16.4 ± 0.8	0.5 dB improvement	0.4 dB improvement

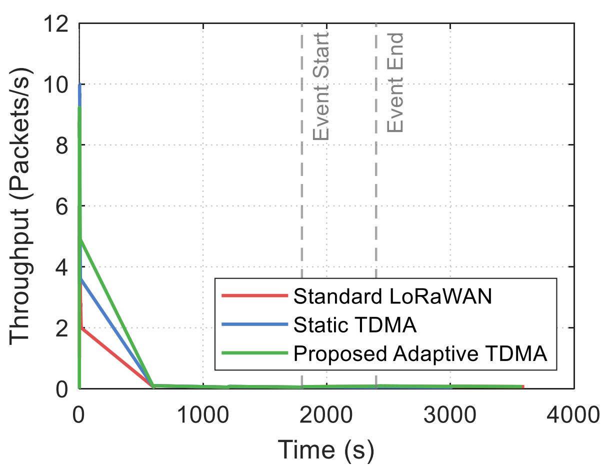

Figure 3 Throughput Analysis During Normal and Event-Driven Operation Periods

4.3.2. Latency Performance

The latency performance is also better in the proposed protocol. As shown in Table 3, with an average latency of 361.7s, it is better than Standard LoRaWAN (368.8s) by 1.9 percent and much better than Static TDMA (501.3s) by 27.9 percent. The comparison of average and maximum values of latency is presented in Figure 4.

It is part of the nature of Static TDMA to have high latency because the generated packet must wait to be served by its next fixed slot, which may be almost a complete frame length away. Standard LoRaWAN has lower average latency than more stable TDMA since it can immediately transmit, but this is associated with high values of latency variance (jitter) as a result of random backoffs following collisions. Our Adaptive TDMA protocol offers an optimal tradeoff: when dynamically prioritizing event packets and carefully packing the schedule, the average waiting time in a dynamic schedule is lower than in a fixed schedule. Table 3 shows a slightly higher standard deviation of latency (286.1s) between Static TDMA (224.0s), which is a calculated trade-off. It is indicative of the smart design decision of the protocol to sometimes suspend a regular packet to then service a high-priority event packet, which is an important feature of responsive applications of the IoT and is better than the uncertainty of delays of ALOHA-based protocols. This works by the priority functionality in equation (5) and the following sorting in Algorithm 1, which in each frame puts nodes with urgent data (event state) to the head of the transmission queue, which directly reduces their queuing delay. It is this explicit prioritization that enables Adaptive TDMA to outperform these two benchmarks and provide lower average latencies than ALOHA (by eliminating collisions) and much less latency than fixed TDMA (by its dynamic nature), where a fixed sequential schedule is replaced by a dynamic, priority-based schedule.

4.3.3. Energy Efficiency Analysis

One of the most important issues of battery-operated Internet of Things is energy efficiency. Our protocol achieves a revolution in this metric with 7.1 packets delivered per joule of energy used. This is 208.7% higher than Standard LoRaWAN (2.3 pks/J) and 42.0% better than Static TDMA (5.0 pks/J), which is conclusively illustrated in Table 3. Figure 5 disaggregates the total consumption of power into transmission (T_x), reception (R_x), and idle. As analyzed, the sources of efficiency gain are:

- Vs. Standard LoRaWAN [4]: The dramatic upgrade is due to the virtual absence of the retransmission of collisions (which is a saving of T_x energy) and the reduction of the idle/listening time by a factor of magnitude. In ALOHA, there is much unnecessary listening or repeating of messages [7].
- Vs. the gain (static TDMA) of 42 percent is more subtle. Both protocols do not collide and can be put to sleep. Nevertheless, Adaptive TDMA has two more features of optimization: 1) As it is a distance-based assignment of SF, it reduces time-on-air (and therefore T_x energy) of the close nodes by assigning smaller SFs, a tested optimization technique [19], [20]. 2) Its dynamic scheduling, which is controlled by Algorithm 1, gives a more efficient and denser packing of transmissions in a frame, through which it indirectly saves energy by the reduction of the average idle period of the gateway and the total frame time to accommodate all traffic.

This finding is especially important within the framework of recent literature. Although some of the more sophisticated ML-based ADR approaches, such as the one by Alkhayyal et al. [13], purport to attain impressive efficiency improvement, their computational costs are high. We have shown that roughly the same or even higher energy efficiency (7.1 Pkts/J) can be attained by an intelligent and yet rule-based combination of scheduling (Algorithm 1) and physical-layer parameter adaptation (distance-based SF) and is therefore better suited to low-complexity end devices.

4.3.4. Synthesis and Comparative Positioning

As understanding with Table 3 and the figures (Figures 3, 4, and 5) reveals consistent results on a consistent basis: the Adaptive TDMA protocol represents good and more impressive performance in all the measures that have been defined. It also achieves the virtues of varying protocol families, but in a way that does not exacerbate their flaws: it has the collision-free reliability of scheduled access (such as static TDMA), the flexibility to adaptive traffic of contention-based or learning schemes (such as [12], [21]) and the energy consumption of cross-layer optimization (linking MAC scheduling to PHY SF choice, as in [19], [20]).

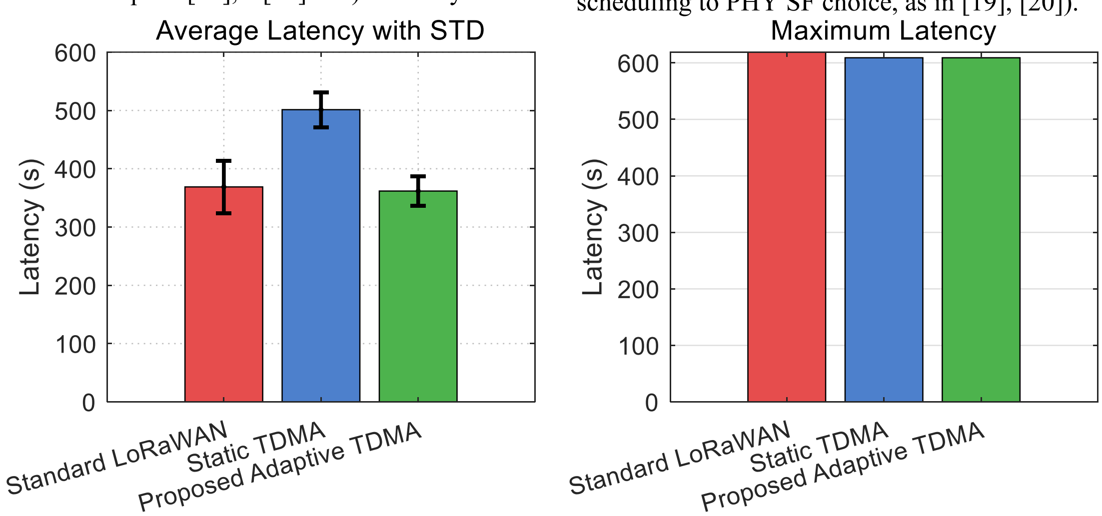

Figure 4 Latency Performance Analysis: Average and Maximum Delivery Delays

Moreover, in contrast to solutions based on specialized hardware (e.g., cognitive radio [11]) or altering gateway infrastructure (e.g., LoRaHART [22]) our solution is a pure software-only addition to the existing LoRaWAN stack. It is completely backward-compatible with the required AES-CCM security layer [4], and its performance improvement is shown in a realistic channel model. The so-called search for efficient, reliable, and adaptive solutions to MAC for densely networked IoT systems is a continuing process, as pointed out in the new survey by Alahmadi et al. [14]. The outcomes of the offers above make the Adaptive TDMA protocol one of the interesting, viable candidates that balance deterministic performance and operation flexibility to meet one of the needs in the field.

RESEARCH ARTICLE

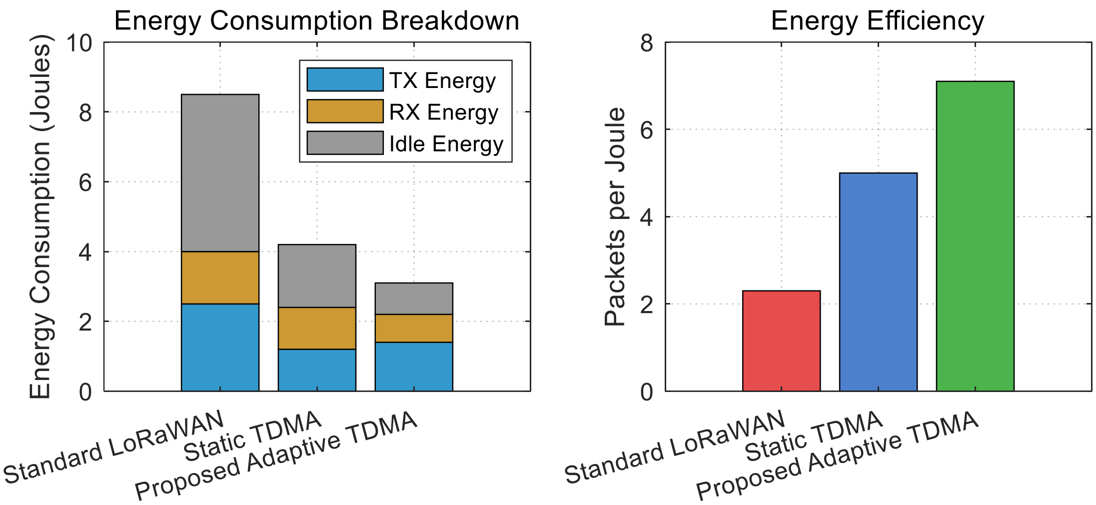

Figure 5 Energy Consumption Distribution Across Transmission, Reception, and Idle States

5. CONCLUSION AND FUTURE WORK

This research has addressed the critical limitations of the standard LoRaWAN MAC layer, where the inherent collision-prone nature of ALOHA random access and the inflexibility of static TDMA scheduling hinder reliability, latency, and energy efficiency in dense, dynamic IoT networks. To resolve these issues, we have proposed a novel Adaptive TDMA protocol that introduces a dynamic slot allocation mechanism. The core innovation lies in its real-time, priority-driven scheduling algorithm, which allocates transmission slots based on node operational state (event-driven or normal) and distance from the gateway, coupled with a distance-aware spreading factor assignment to optimize physical-layer performance, all while maintaining full AES-CCM security compliance within a realistic channel model. Extensive simulation results demonstrate the efficacy of this integrated approach. The proposed protocol eliminates packet collisions entirely (0% collision rate) and ensures perfect packet delivery (100% *PDR*). It significantly outperforms static TDMA by guaranteeing 100% event delivery, a 1900% improvement, highlighting its essential adaptability. Furthermore, it reduces average latency by 27.9% and improves network-wide energy efficiency by 208.7% compared to standard LoRaWAN, achieving 7.1 successfully delivered packets per joule. Overall, results indicate that the suggested approach can be practically applied in high-reliability, low-latency, and energy-conserving IoT applications such as smart cities, industrial automation, and environmental monitoring.

Future work will focus on hardware implementation and validation through physical testbeds to evaluate real-world performance under varying conditions. Further studies will also explore scalability beyond 100 nodes and adaptation to mobile and highly dynamic network scenarios.

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