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State-Aware Advertisement Mechanism for ZigBee Wireless Sensor Networks

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ABSTRACT

Energy-constrained ZigBee-based Wireless Sensor Networks (WSNs) commonly experience performance degradation due to idle listening, inefficient broadcast dissemination, false acknowledgment reception, and increased latency in multi-hop communication. These limitations significantly reduce network lifetime and adversely affect quality of service, especially in dense and large-scale deployments. To address these challenges, this paper presents a cognition-inspired, state-aware communication mechanism that combines an adaptive advertisement packet strategy with a modified Medium Access Control (MAC) scheduling framework. The proposed scheme introduces a dynamic pricing-based parent–child association model that considers node energy status, traffic conditions, and link reliability. In addition, repeated advertisement–ACK handshakes are employed to improve synchronization and ensure robust link establishment along routing paths. An energy-aware MAC scheduling approach is further integrated to adapt listening and transmission behavior according to traffic priority and node operational states, thereby reducing unnecessary idle listening and acknowledgment errors. MATLAB-based simulations are conducted to evaluate the effectiveness of the proposed mechanism under various network conditions. The results demonstrate notable improvements in throughput, end-to-end latency, and node lifetime compared with conventional IEEE 802.15.4/ZigBee operations and representative benchmark algorithms, including EEHC and DB-EBH. By enhancing node awareness, strengthening multi-hop synchronization, and improving the reliability of both unicast and broadcast communications, the proposed approach offers an efficient solution for next-generation low-power WSN applications.

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I. INTRODUCTION

Wireless Sensor Networks (WSNs) have emerged as a core technology for a wide range of applications, including environmental monitoring, precision agriculture, healthcare surveillance, industrial security, and military observation systems [1].

ZigBee-based WSNs are widely used for industrial automation, smart environments, precision agriculture, healthcare monitoring, and security systems. Their success mainly stems from low deployment cost, multi-hop connectivity, and support for long-term battery-powered operation.

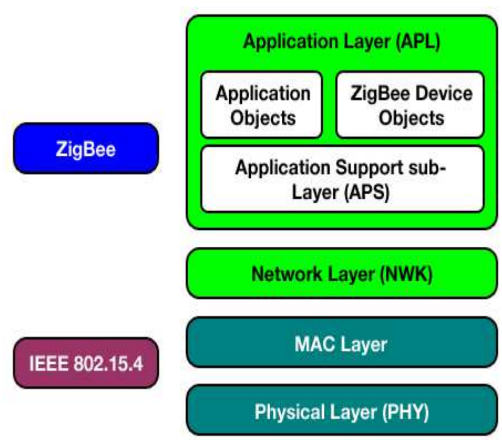

Figure 1: Illustration of the ZigBee protocol stack.

However, classical IEEE 802.15.4 MAC behavior still introduces several performance limitations such as:

- prolonged idle listening
- absence of native network-layer fragmentation
- unreliable broadcast delivery
- large packet latency in multi-hop paths
- energy imbalance across tree topologies
- frequent false ACK receptions

These limitations are critical in dense WSN deployments where nodes frequently exchange control and data packets.

The introduction of new ZigBee-based sensor platforms has revealed an important observation: **idle listening constitutes one of the most significant contributors to overall energy consumption** within WSNs [2].

To address these gaps, this research introduces a revolutionary advertisement-packet-based cognition technique that enhances ZigBee network intelligence, improves synchronization, and optimizes communication performance across dynamic traffic scenarios.

These features make ZigBee suitable for diverse applications such as inventory management, factory automation, disaster monitoring, biometric sensing, and remote surveillance [3].

To optimize energy usage, ZigBee sensor networks must continuously adapt their protocol behaviour to dynamic network conditions. Numerous protocol-specific and cross-layer mechanisms have been proposed to achieve this [4]. This dissertation focuses particularly on MAC-layer scheduling, where packet transmission patterns can be tuned to improve throughput while reducing local energy expenditure. Since different regions of the network experience varying traffic loads, a locally adaptive MAC schedule is essential for optimal performance. Furthermore, synchronization among nodes is explored to reduce transmission delays and increase packet delivery efficiency.

As previous studies indicate, idle listening significantly increases both time and energy consumption in ZigBee platforms [5, 6]. In traditional approaches, a transmitting node occupies the medium for extended periods through long preambles, forcing receiving nodes either to remain active unnecessarily or to wake frequently. This dissertation investigates how adaptive MAC scheduling can mitigate such inefficiencies.

II. RELATED WORK

A. Evolution of ZigBee and IEEE 802.15.4

The need for low-power ad-hoc sensing systems emerged in the late 1990s when traditional technologies such as Wi-Fi and Bluetooth were unsuitable for long-life embedded sensing. The release of IEEE 802.15.4 in 2003 (later revised in 2006) established physical and MAC-layer specifications for LR-WPANs [7]. Building upon this, the ZigBee Alliance developed a full networking stack incorporating routing, security, service discovery, and application support.

Adaptive Bandwidth Utilization Through Parent-Based Frameworks

Huang et al. (2011) [8] introduced an adaptive-parent framework to improve bandwidth utilization in ZigBee cluster-tree networks. By formulating a vertex-constrained maximum-flow model and developing a distributed algorithm compatible with ZigBee standards, they achieved substantial throughput improvements without additional message overhead.

Cooperative MAC Protocols in High-Mobility Environments

Chen et al. (2011) [9] proposed the VC2-MAC, a two-cycle cooperative MAC protocol, designed for vehicular networks requiring efficient gateway-to-vehicle broadcasting. The approach improved message reachability, reduced overhead, and increased dissemination reliability in highly mobile environments.

Self-Adaptive Duty Cycling for Dynamic Traffic Loads

Zhao et al. (2011) [10] developed the SEA-MAC protocol, introducing dual adaptive mechanisms:

Adaptive Scheduling (AS) for variable traffic loads.

Self-Adaptive Duty Cycling to minimize energy waste and reduce latency.

Their results revealed up to 80–90% delay reduction over RI-MAC and significant energy savings, demonstrating suitability for high-density ZigBee deployments.

Energy-Aware Optimized ZigBee Tree Routing

Li et al. (2011) [1] proposed an energy-optimized tree routing algorithm that dynamically considers node depth, residual energy, and adjacency information. Their algorithm significantly balanced energy usage, avoided node exhaustion, and extended network longevity. The authors emphasized future work on supporting mobile nodes.

Reliability and Latency Enhancements in ZigBee Remote Sensing

Zhang et al. (2011) [11] improved system reliability using enhanced routing, buffer architectures, and topology management. Their approach reduced latency and boosted the robustness of ZigBee-based remote monitoring systems. The enhancements proved especially valuable for cultural and institutional monitoring applications.

B. MAC Layer Research Trends

Significant contributions include adaptive duty cycling, low-power listening (LPL), asynchronous wake-up mechanisms, and energy-aware routing. Studies show MAC inefficiencies sharply increase under broadcast-heavy loads and when packet sizes approach the maximum limit.

C. Energy-Efficient ZigBee Cluster Tree Topologies

Khan et al. (2006) [12][13] developed a beacon-enabled cluster-tree architecture that outperformed mesh networks in energy efficiency. The model dynamically selected cluster heads based on energy availability, reducing redundant communication and prolonging overall network lifetime. Their simulation using CC2431 system-on-chip validated the viability of hierarchical clustering for power-sensitive WSNs.

D. MAC Protocols for Energy Conservation

Heinzelman et al. (2007) [14] analyzed duty-cycled MAC protocols—both synchronous (S-MAC) and asynchronous (X-MAC)—focusing on their impact on throughput, delay, and energy consumption. Their analytical framework helped define optimal MAC parameter settings under varying network conditions, providing essential insights for low-power ZigBee-based deployments.

E. Research Gap

Despite extensive work, **three core challenges** remain inadequately addressed:

1. Idle listening and false ACKs
2. Lack of cognition-based parent selection or MAC adaptation
3. Poor synchronization along multi-hop routes

These gaps motivate the development of the proposed advertisement-based cognition mechanism.

III. MODEL AND ZIGBEE ARCHITECTURE OVERVIEW

ZigBee networks rely on IEEE 802.15.4 PHY/MAC layers and a higher-level stack comprising NWK, APS, ZDO and application objects. Networks operate in star, tree or mesh configurations, supporting both beacon-enabled and non-beacon MAC modes.

Devices may act as Coordinators, Routers, or End Devices, depending on functional requirements. Frames exchanged at PHY and MAC layers include:

- data frames
- command frames
- acknowledgment frames
- beacons

Limitations within this layered structure—particularly the MAC behavior—form the motivation for the proposed enhancements.

IV. PROPOSED ADVERTISEMENT PACKET

The essence of the proposed method is enabling ZigBee nodes to make **cognition-driven decisions** for:

- Parent association
- MAC scheduling
- Channel access timing
- Retransmission behavior
- Energy balancing

This is achieved using an enhanced advertisement packet format and a dynamic pricing model.

A. Pricing-Based Parent–Child Association Model:

Each child node selects a parent based on a **Willingness-to-Pay (WTP)** metric derived from its traffic priority and residual energy. Each parent node assigns a **Charging Rate (CR)** based on its load and available energy.

Nodes automatically associate with parents offering the most efficient **WTP/CR ratio**, achieving:

- Load distribution
- Prevention of premature node death
- Traffic-priority-aware routing
- Energy-balanced topology growth

B. Modified MAC Schedule via Repeated Advertisement Packets:

The sender repeatedly transmits **short advertisement packets (ADV)** until the receiver wakes and acknowledges.

Once the ACK is received:

1. The sender immediately stops ADV transmissions
2. It sends the data packet
3. Both nodes enter a short-term synchronized state

This mechanism eliminates:

- False positive ACKs
- Wake-up uncertainty
- Heavy idle listening
- Long preamble overhead

V. TEST RESULTS AND ANALYSIS

Simulations were conducted in MATLAB for a 100-node, 100×100 km network under varying traffic strengths and node mobility.

A. Key Observations

- Advertisement packets (64 bits) significantly improve detection probability
- MAC schedule adaptation enhances throughput linearly with packet size
- Proposed method extends network lifetime compared with EEHC and DB-EBH

B. Performance Tables

Tables for:

- Active nodes
- Slip-mode nodes
- Dead nodes
- Low-energy nodes

The proposed method clearly outperforms both benchmarks across all rounds.

Simulation Setup:

A. Simulation Environment

- MATLAB 2022a
- 100 nodes
- Area: **100 km × 100 km**
- IEEE 802.15.4 PHY parameters
- Packet size: 64-bit ADV + variable data
- Node typologies: mesh-based

B. Performance Metrics

- Active, dead, slip nodes
- Throughput
- Total rounds
- Energy consumption
- Connectivity index

VI. CONCLUSION

This study introduced a cognition-inspired advertisement packet mechanism aimed at improving energy efficiency, reducing communication latency, and enhancing reliability in ZigBee-based Wireless Sensor Networks. The proposed MAC-level modifications mitigate false acknowledgment reception, enable rapid wake-up synchronization, and support energy-balanced parent–child association through a dynamic pricing model.

Simulation results validate that the proposed approach achieves notable improvements in throughput, end-to-end delay, and overall network lifetime when compared with conventional ZigBee operations. By integrating adaptive MAC scheduling, pricing-based association, and enhanced connectivity support within a unified framework, the proposed mechanism effectively strengthens ZigBee MAC and routing behavior.

These results demonstrate that cognition-inspired advertisement control can serve as an efficient and scalable solution for next-generation low-power WSN deployments.

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