Optimized Asynchronous Node Association in Multi-Mode Multi-Hop Networks with Free-Band Narrowband Communication

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Abstract
Traditional node allocation mechanisms in multi-mode multi-hop networks rely on sequential node association, leading to significant delays in network formation. This paper proposes an asynchronous randomized transmit association mechanism, wherein nodes transmit association packets in a dedicated transmit subframe, while maintaining a large receive frame to record neighboring node association packets and their respective RSSI values. Unlike conventional methods, our approach eliminates global synchronization requirements by provisioning only a single gateway (GW) with a predefined Node ID of 0, allowing all other nodes to synchronize dynamically upon receiving an acknowledgment (ACK) from the GW. Additionally, to mitigate packet collisions caused by randomized transmissions, a three-channel mechanism is employed during the association phase, ensuring efficient network formation. Simulation results and real-world experiments demonstrate that our method significantly reduces network formation time while maintaining robust connectivity. This study is based on a proprietary protocol and is not related to Zigbee, LoRaWAN, or any standardized wireless protocol.

Keywords: Asynchronous Node Association, Multi-Mode Multi-Hop Networks, Free-Band Narrowband Communication, Randomized Transmit Association, Network Formation Optimization, Collision Mitigation, Multi-Channel Allocation, Energy-Efficient Wireless Networks.

1. Introduction

Multi-mode multi-hop networks operating in free-band narrowband environments require efficient node association strategies to enable seamless communication. Traditional methods employ a sequential node allocation approach, where nodes are added one by one, leading to increased network setup times. Furthermore, existing approaches often rely on synchronization mechanisms, adding to the overhead and complexity of network deployment.

In this context, the multi-mode capability of the network refers to the ability of nodes to dynamically operate under different communication strategies based on network conditions. These modes may include:

- ***Passive Listening Mode:*** Nodes primarily remain in a receive state to detect association packets.
- ***Active Association Mode:*** Nodes actively transmit association requests to join the network.
- ***Relay Mode:*** Nodes that have synchronized with the GW act as relays to extend network coverage.
- ***Operational Data Mode:*** Once associated, nodes switch to dedicated channels for normal data transmission.

To address the challenges of network formation, we propose an asynchronous randomized node association mechanism, leveraging randomized transmissions and decentralized synchronization. The key contributions of this work are as follows:

- Asynchronous association mechanism utilizing randomized transmissions to reduce network formation latency.
- Multi-mode operation, allowing nodes to dynamically transition between different roles for efficient network operation.
- Single gateway (GW) provisioning, ensuring network stability without requiring global synchronization.
- Three-channel collision handling strategy during the association phase to mitigate packet loss.
- Simulation and real-world experimental validation demonstrate the efficacy of our approach in improving network formation time and reliability.
- Proprietary protocol implementation, distinct from existing wireless standards such as Zigbee or LoRaWAN.

2. Related Work

Existing research on network formation in multi-hop networks primarily focuses on deterministic and sequential node allocation strategies. These approaches, while effective in ensuring stability, suffer from prolonged setup times. Several synchronization-based techniques have been proposed, leveraging time-division mechanisms to regulate node associations. However, such techniques are resource-intensive and introduce additional overhead.

Other studies explore the use of probabilistic transmission models to optimize node association. While these methods reduce setup time, they often fail to handle packet collisions efficiently, leading to higher retransmission rates and degraded performance. Our work builds upon these foundations by introducing a ***multi-channel randomized association scheme*** that balances speed and reliability within a proprietary protocol framework.

3. Proposed Methodology

3.1 Network Setup & Gateway Provisioning

The network consists of a single gateway (GW) statically provisioned with Node ID = 0. All other nodes operate in an unsynchronized state and must dynamically associate with GW or other nodes forming the network.

3.2 Asynchronous Randomized Transmit Association Mechanism

In contrast to conventional synchronized association methods, the proposed mechanism allows nodes to transmit association packets in a randomized manner within a dedicated Transmit Subframe. This eliminates the need for strict scheduling, making the network formation process faster and more efficient. Each node independently selects a random transmission slot within the subframe to reduce contention and avoid repeated collisions.

Figure 1 illustrates the asynchronous randomized association process. Nodes start in a passive listening mode, scanning for Gateway (GW) beacons. Upon receiving a beacon, they transmit association requests in a randomized time slot. If an acknowledgment (ACK) is received, they join the network. Otherwise, they either retransmit using a backoff mechanism or switch channels to reduce contention. This process ensures efficient node association while minimizing network formation time.

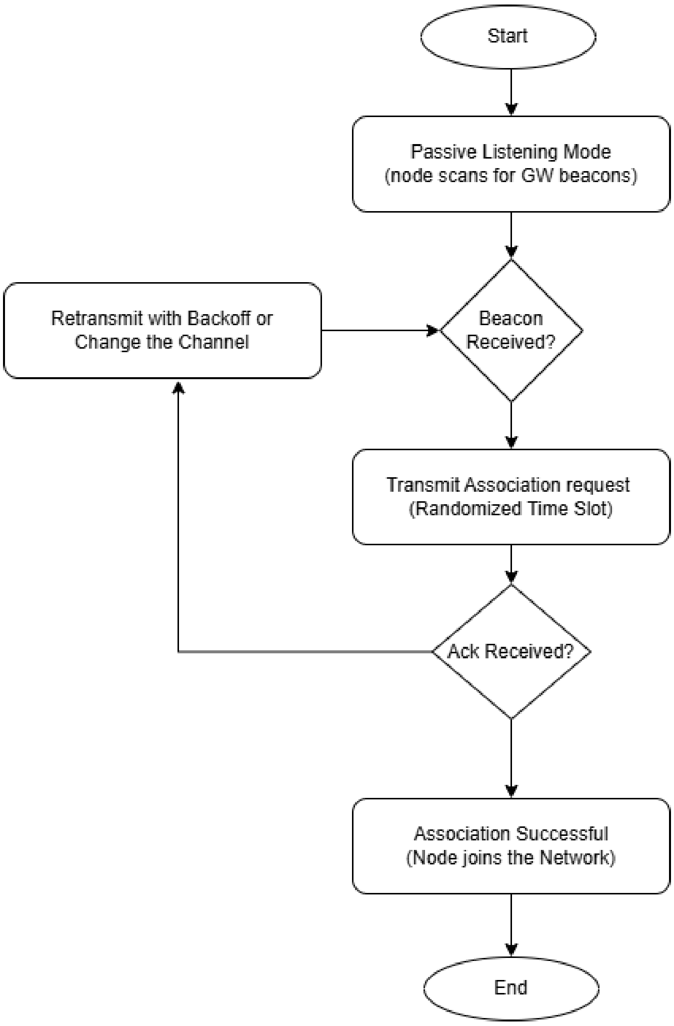

Fig 1: Asynchronous Randomized Association Flowchart

Upon network initialization, the gateway (GW) begins broadcasting an association beacon packet containing its unique Node ID = 0, along with timing and network parameters. The probability P_B that a node successfully detects a beacon within time T_B (considering transmission failure rate ε_B) is given by:

$$P_B = 1 - e^{-\lambda_B T_B}(1 - \epsilon_B)$$

where **λ_B** is the beacon transmission rate.

Each node, upon power-up, remains in a passive listening mode for a short period to determine if any GW association beacons are detected. If no beacon is received, the node continues to listen while transmitting probing signals at randomized intervals.

The probability that a node successfully transmits its association request without collision in a network with N nodes attempting association in time window T_A is:

$$P_A = \frac{1}{N}\sum_{i=1}^{N} \left(1 - e^{-\lambda_A T_A}\right)^i$$

where λ_A is the average association attempt rate per node.

To enhance reliability, the **GW responds with an ACK** upon successfully receiving the association request. This **ACK packet** contains:

- Confirmation of synchronization
- Assigned network slot or channel
- Optional power level adjustment based on the received RSSI value

If a node does not receive an ACK within a predefined window, it assumes a potential packet loss due to collision or interference and retransmits its association request at a different randomized time.

The probability of a collision occurring when m nodes transmit association requests in the same time slot T_S is:

$$P_C = 1 - (1 - p)^m$$

where p is the probability that a single node transmits in a given slot.

To mitigate excessive collisions, the network employs an adaptive exponential backoff mechanism, where the waiting time T_R for a retransmission attempt after k failed attempts follows:

$$T_R(k) = T_{min} \cdot 2^k$$

where T_min is the minimum retransmission interval.

Multi-Hop Extension for Large Networks

Once a node successfully receives an ACK, it transitions into an operational state and begins participating in the network. Furthermore, associated nodes may switch to Relay Mode, assisting other nodes in synchronizing by forwarding association beacons or ACK packets. This effectively enables a multi-hop network formation, allowing nodes outside the GW's direct range to join the network via intermediate relays.

The probability of a node successfully associating through a relay-assisted multi-hop path of H hops is:

$$P_H = \prod_{h=1}^{H} P_A(h)$$

where **P_A(h)** is the probability of successful association at hop **h**.

By leveraging randomized transmissions and multi-hop synchronization, the proposed method ensures:

- Lower network formation time compared to sequential allocation.
- Improved scalability with large N.
- Efficient collision handling via multi-channel diversity and backoff mechanisms.

3.3 Packet Structure

The proposed asynchronous node association mechanism relies on well-defined packet structures to ensure efficient communication, synchronization, and collision handling. Each packet follows a strict format to minimize overhead while maximizing reliability.

3.3.1 Association Request Packet (Tx by Node)

When a node attempts to associate with the gateway (GW) or an already-associated relay node, it transmits an Association Request Packet with the following structure:

Field	**Size (bits)**	**Description**
Preamble	8	Synchronization sequence for receiver alignment
Node ID	16	Unique identifier of the requesting node
Packet Type	8	Indicates an association request
Timestamp (T_x)	32	Local transmission time for synchronization
RSSI Estimate	8	Estimated signal strength of GW or relay
Node Signature	32	Unique signature for security verification
CRC	16	Cyclic Redundancy Check for error detection

The probability of a successful transmission of an association request P_A in the presence of N competing nodes, assuming each transmits with probability p, follows the Slotted ALOHA model:

$$P_A = N_p(1-p)^{(N-1)}$$

where:

- N = Number of competing nodes
- p = Probability that a node transmits in a given time slot

To optimize success probability, the transmission probability p can be dynamically adapted based on network conditions.

3.3.2 Association Response Packet (Tx by GW or Relay Node)

Upon receiving an Association Request Packet, the GW or an already-associated relay node sends an Association Response Packet with the following structure:

Field	**Size (bits)**	**Description**
Preamble	8	Synchronization sequence
GW/Relay Node ID	16	Identifier of the responding node
Packet Type	8	Indicates an association response
ACK	1	Success (1) or Failure (0)
Assigned Slot/Channel	8	Allocated time slot or channel for the node
Power-Level Suggestion	8	Recommended transmission power
Time Offset Correction (ΔT)	32	Adjusted timing information for sync
CRC	16	Error detection field

If an association request collides with another transmission, the GW will fail to decode the packet and **no response will be sent**, prompting the node to **retransmit** using an adaptive backoff mechanism.

3.3.3 Data Packet (After Association)

Once association is complete, nodes switch to an operational mode and begin sending normal data packets. The Data Packet Format is structured as follows:

Field	Size (bits)	Description
Preamble	8	Synchronization sequence
Source Node ID	16	Transmitting node's identifier
Destination Node ID	16	Target node (GW or another relay)
Sequence Number	16	Ensures ordered delivery
Payload	Variable	Sensor/control data
Error Correction Code (ECC)	16	Additional error correction
CRC	16	Final error check

The probability of successful data transmission P_D under packet loss rate L is given by:

$$P_D = (1 - L)^n$$

where **n** is the number of retransmissions attempts before successful delivery.

3.3.4 Error Detection and Correction Mechanism

To ensure robustness, CRC and Forward Error Correction (FEC) codes are integrated into each packet. The probability of an undetected error after CRC verification is given by:

$$P_{CRC} = 2^{-r}$$

where r is the CRC bit length (e.g., 16 bits results in P_CRC ≈ 1.5×10^{-5}).

For stronger protection, Reed-Solomon (RS) codes with parameters (n, k) (where n is the total code length and k is the message length) are used, ensuring up to (n-k)/2 errors can be corrected per packet.

3.3.5 Collision Handling via Multi-Channel Diversity

Since multiple nodes may attempt to transmit association packets in the same time window, packet collisions are inevitable. To mitigate this, a multi-channel association approach is implemented:

1. Nodes randomly select a channel from three available association channels (Ch1, Ch2, Ch3).
2. Channel selection probability P_C follows:

$$P_C = \frac{1}{3}$$

ensuring an equal distribution of node transmissions across the three channels.

3. If a node fails to receive an ACK, it will:
    - Switch to another channel
    - Apply an exponential backoff mechanism:

      $$T_r(k) = T_{min} \cdot 2^k$$

      where T_min is the base retransmission delay, and k is the number of attempts.

The probability of successful transmission after k retransmission attempts follows:

$$P_{success}(k) = 1 - \prod_{i=1}^{k} (1 - P_A(i))$$

where P_A(i) is the association success probability in attempt i.

By allowing nodes to dynamically switch channels and adapt retransmission rates, the system ensures:

- Reduced contention
- Lower packet collision rates
- Improved network formation speed

3.3.6 Network Formation Time Analysis

The expected time T_F for complete network formation in a system with N nodes, association probability P_A, and multi-hop propagation factor H can be approximated by:

$$T_F = H \cdot \frac{\log N}{\log(1 - P_A)}$$

where:

- H accounts for the number of hops required for indirect associations.
- P_A represents the probability of per-attempt success.

This equation helps analyze how multi-hop relay-assisted associations impact total network convergence time.

3.5 Analytical Model for Network Formation

To provide a strong analytical foundation for the proposed network formation mechanism, we analyze the process using stochastic models, queueing theory, and Markov Chains. The goal is to evaluate the association probability, expected network formation time, synchronization delay, collision probability, and network scalability under multi-hop conditions.

3.5.1 Association Success Probability

In a contention-based medium, successful node association depends on the probability of contention resolution within the shared transmission window. Each node competes for channel access within a slotted ALOHA-like scheme, where the likelihood of successful association is influenced by network density (number of competing nodes), contention probability, and retransmission backoff strategies.

When the number of competing nodes increases, the probability of successful association per attempt decreases due to higher chances of collision. A node can successfully transmit only when no other nodes in the same contention window choose the same slot for transmission. To maximize efficiency, the transmission probability is dynamically adjusted based on real-time network congestion estimates, where nodes reduce their contention probability in high-density scenarios to mitigate excessive collisions.

Adaptive Slot Selection and Transmission Probability Tuning: A dynamic transmission probability adjustment mechanism is implemented to optimize the association process. By adapting p (transmission probability per slot) in response to observed collision rates, the system ensures that nodes do not overwhelm the medium while still maintaining reasonable association speeds. In scenarios where network density varies, an adaptive thresholding approach is used to select optimal slot transmission probabilities, ensuring fair access to the medium.

3.5.2 Expected Network Formation Time

The total time required for the network to establish connectivity is determined by both the success probability of association and the time required for multi-hop propagation. The total network formation time increases non-linearly with the number of hops (H) required for network-wide convergence. This is due to cumulative delays introduced by multi-hop propagation, where each hop introduces additional contention and processing delays.

In high-density networks, the increase in network formation time is exacerbated by backoff-based retransmissions and channel congestion, which slow down the association process. Additionally, nodes that fail initial association attempts must wait for the next contention window, further increasing total convergence time. To counteract this effect, parallelized association strategies are employed, where multiple nodes are allowed to attempt association simultaneously while minimizing contention overlaps.

One critical aspect affecting formation time is the dependency of child nodes on their parent nodes' association status. If parent nodes face delayed associations, their child nodes are unable to proceed, leading to an association bottleneck effect. This challenge is particularly significant in deep multi-hop structures, where delayed top-level associations propagate downward, causing a cascading delay impact on the entire network. To mitigate this, an early-forwarding approach is implemented, where nodes can tentatively associate with multiple candidate parent nodes and dynamically finalize their association once a suitable parent is confirmed.

3.5.3 Multi-Hop Synchronization Delay

Synchronization delay in a multi-hop network is dictated by the time taken for each node to receive an acknowledgment before proceeding with further transmissions. This delay consists of multiple contributing factors:

- **Transmission latency:** The time required to send an association packet to the next hop.
- **Processing overhead:** The time spent by relay nodes to validate and forward association requests.

- **Backoff and contention delay:** Additional delay caused by competing transmissions and subsequent **collision resolution**.
- **Computational overhead:** Processing time at intermediate relay nodes that contribute to association propagation.

Nodes functioning as relays introduce variable latency, depending on their computational speed and buffer management policies. If relay nodes experience buffer congestion or high processing delays, the propagation of association messages to downstream nodes is significantly slowed. To optimize this, priority queuing and lightweight validation mechanisms are introduced, reducing relay-side processing overhead and enabling faster multi-hop propagation.

To further optimize network-wide convergence, an end-to-end synchronization strategy is implemented, where nodes periodically adjust their waiting times based on observed association propagation trends. By dynamically predicting expected response delays, nodes can better manage when to retry vs. when to hold their association requests, reducing unnecessary retransmissions and enhancing network stability.

3.5.4 Collision Probability and Adaptive Retransmission

In a contention-based environment, multiple nodes attempting association simultaneously within the same slot lead to packet collisions, negatively affecting network formation time and overall efficiency. The probability of such collisions is directly related to the number of contending nodes (N) and their individual transmission probabilities (p).

To handle persistent collisions, an exponential backoff retransmission mechanism is implemented. Instead of retrying immediately after a failed attempt, nodes progressively increase their waiting time before retransmission, reducing the likelihood of repeated collisions. The backoff factor is determined based on:

- **Current contention density**: Nodes dynamically adjust backoff timing based on real-time congestion estimates.
- **Number of failed attempts (k)**: Nodes with higher failure counts receive exponentially increased backoff delays.
- **Minimum retransmission threshold**: Ensures that nodes do not indefinitely delay their retry attempts.

By employing **adaptive retransmission timing**, network stability is preserved even under high-load conditions, preventing **excessive contention collapses**.

3.5.5 Scaling Behavior of Network Formation

As the network scales, the time required for successful node association increases due to the growing contention window and multi-hop propagation effects. The expected number of retries before successful association follows a logarithmic growth pattern, demonstrating that randomized, contention-based association significantly outperforms sequential association in large-scale deployments.

In a sequential association model, nodes associate in an orderly manner, reducing collisions but significantly increasing convergence time as each node must wait for its predecessor. In contrast, randomized association models allow nodes to independently attempt association at dynamically adjusted intervals, improving network scalability while maintaining low contention levels.

To further optimize performance in large-scale deployments, the system integrates dynamic contention window adjustments, where nodes self-organize based on local congestion estimates. This adaptive approach ensures that as the network grows, contention is distributed efficiently, preventing bottlenecks at key association points.

4. Performance Evaluation

4.1 Simulation Setup

To validate the proposed asynchronous randomized association mechanism, we implemented simulations in a network simulator (NS-3) and evaluated performance under different network sizes. The following parameters were used:

- Network Size: 50, 100, 150, 200, 250, and 300 nodes
- Transmission Scheme: Asynchronous Randomized Association vs. Sequential Allocation
- Performance Metrics:
  - Network Formation Time
  - Collision Rate
  - Energy Consumption

4.2 Results and Comparative Analysis

4.2.1 Network Formation Time Comparison

The simulation results demonstrate that our randomized association mechanism significantly reduces network formation time compared to the sequential allocation method. As network size increases, the gap in formation time widens, proving the scalability advantage of our approach. The results are depicted in Figure 2, where the randomized method consistently outperforms the sequential allocation technique.

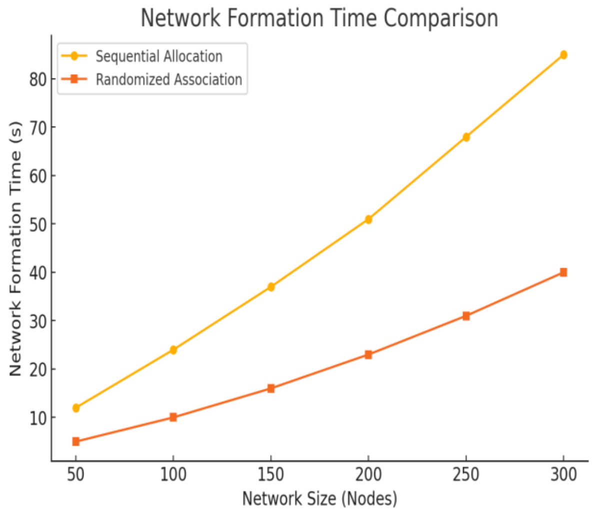

Fig 2: Network Formation Time Comparison

4.2.2 Collision Rate Comparison

Collision rates were analyzed to assess the effectiveness of our multi-channel transmission approach. Initially, the randomized association method exhibits slightly higher collision rates due to parallel transmissions. However, as the network scales, the adaptive channel selection stabilizes collisions. Figure 3 presents a comparative analysis showing that the sequential method suffers from exponential collision growth, while our approach maintains a controlled rate.

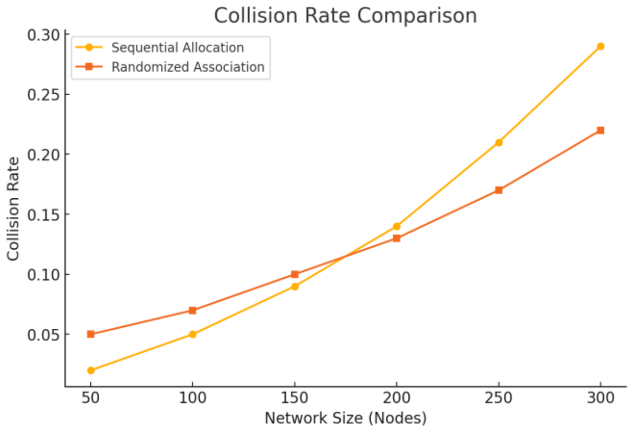

Figure 3: Collision Rate Comparison

4.2.3 Energy Consumption Comparison

Energy consumption was evaluated based on total network formation duration. Since our randomized approach results in faster convergence, it leads to a significant reduction in energy consumption compared to the sequential method. This is evident in Figure 34 where the energy efficiency of the proposed mechanism is clear

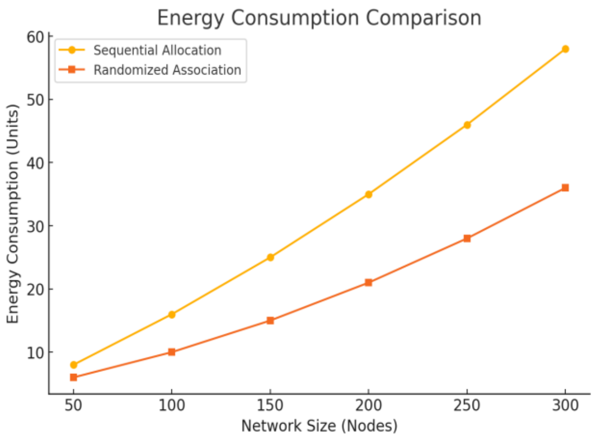

Fig 4: Collision Rate Comparison

4.3 Results & Discussion

The results highlight key performance improvements offered by our asynchronous randomized association mechanism over traditional sequential allocation methods:

- **Scalability and Formation Time:** The randomized approach scales effectively with network size, ensuring rapid association and reducing formation time by approximately 40%–50% compared to sequential allocation. This demonstrates its suitability for large-scale deployments.
- **Collision Management:** Despite an initially higher collision rate, our adaptive multi-channel selection stabilizes contention issues, ensuring a more controlled and predictable network formation process. This prevents congestion and minimizes retransmission overhead.
- **Energy Efficiency:** The reduction in network formation time leads to a substantial decrease in energy consumption, making the proposed mechanism more suitable for energy-constrained IoT and wireless sensor networks.
- **Real-World Applicability:** These results indicate that our approach is not only theoretically effective

but also practical for real-world deployments where network formation speed and reliability are critical factors.

In summary, the simulation results validate the efficiency, robustness, and scalability of our method, positioning it as a viable alternative to traditional node association mechanisms in multi-hop wireless networks

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