Physical Antenna Diversity and Fixed-Slot Scheduling for Robust Narrowband Wireless Communication in Free Spectrum

Anand Kumar Singh[1], Omkar Wagle[2]

[1]Esencia Tech, CA, [2]D

Abstract

The Antenna diversity is a critical technique for enhancing the reliability of narrowband wireless communication in the free spectrum, particularly in multi-node and multi-hop mesh networks. This study explores the effectiveness of physical antenna diversity combined with software-based mechanisms for antenna selection in mitigating challenges such as multipath fading, interference, and limited bandwidth. The focus is on leveraging historical Received Signal Strength Indicator (RSSI) data to optimize antenna selection for transmission (TX) and reception (RX) in fixed-slot scheduling. The implementation of these strategies in multi-node mesh networks is discussed, considering hardware requirements, software architecture, and power management. The impact of antenna diversity on reliability was demonstrated through improved signal quality, reduced packet loss, and scalability. Case studies on IoT mesh networks, industrial automation, and environmental monitoring have highlighted the practical applications of these techniques. Challenges and future directions, such as integration with legacy systems, adaptation to dynamic environments, and the potential for advanced techniques, such as machine learning and Massive MIMO, are also addressed. This study concludes that physical antenna diversity coupled with RSSI-based selection mechanisms and fixed-slot scheduling offers a robust solution for efficient and dependable communication in diverse narrowband wireless applications.

Keywords: Antenna Diversity, Narrowband Wireless Communication, RSSI-Based Antenna Selection, Multi-Hop Mesh Networks, Fixed-Slot

1. Introduction

The increasing reliance on narrowband wireless communication in the free spectrum for applications like Internet of Things (IoT), industrial automation, and remote monitoring has heightened the need for reliable connectivity. Narrowband systems, such as LoRa and Sigfox, have been widely adopted for their long-range capabilities and low power consumption, but they face significant challenges due to interference and multipath effects. Historically, antenna diversity has been a proven strategy in mitigating such issues, initially used in cellular systems to ensure consistent signal quality and now adapted for narrowband applications. Despite its advantages, narrowband communication suffers from challenges such as interference, multipath fading, and limited spectral resources. Physical antenna diversity, supported by intelligent software algorithms, offers a promising solution to these challenges by enabling optimal antenna selection based on channel conditions.

This paper presents an overview of physical antenna diversity techniques and their implementation in fixed-slot, multi-node, multi-hop mesh networks. The discussion emphasizes the use of RSSI data to determine the best antenna for each communication event, ensuring efficient and robust operation.

2. Fundamentals of Antenna Diversity

The Antenna diversity involves the use of multiple antennas to exploit spatial and temporal variations in the wireless channel. In this context, physical diversity is particularly important, leveraging spatial separation and polarization differences to achieve uncorrelated signal paths. For instance, in a multi-node environment, spatial diversity can be achieved by placing antennas at carefully calculated distances to minimize correlation. Polarization diversity, on the other hand, can utilize vertical and horizontal antenna polarizations to maintain consistent signal quality in the presence of multipath reflections. A practical example could be a dual-antenna IoT device where one antenna is optimized for near-ground reflections and the other for higher-altitude paths. A diagram illustrating these setups can help visualize how spatial and polarization diversity work in tandem. Key diversity techniques include:

- **Spatial Diversity**: Employing antennas placed at different locations to capture uncorrelated signals.
- **Polarization Diversity**: Using antennas with different polarization orientations to mitigate signal degradation.

In narrowband systems, diversity is complemented by software mechanisms that select the optimal antenna based on metrics such as RSSI, signal-to-noise ratio (SNR), or link quality.

Narrowband communication systems operate within a small frequency range, making them vulnerable to:

- **Multipath Fading**: Signal reflections causing destructive interference and signal attenuation**.**
- **Limited Bandwidth**: Restricting data rates and increasing susceptibility to noise.
- **Interference**: Overlap with other devices in the free spectrum leading to degraded signal quality

These challenges are exacerbated in multi-node, multi-hop mesh networks where communication reliability depends on robust link management across numerous nodes.

3. Antenna Selection Mechanism

3.1. RSSI-Based Antenna Selection

The RSSI-based antenna selection process ensures that each node in the network dynamically selects the best antenna for optimal signal quality during its designated time slot. The process is outlined in Figure 1.

- **Wait for Transmit/Receive Slot:** Each node remains idle until its assigned time slot begins, as defined by the fixed-slot scheduling mechanism.
- **Analyze RSSI History:** The node evaluates historical RSSI data to identify trends in signal strength across its antennas.
- **Select Best Antenna**: Using the data analyzed, the node determines which antenna provides the strongest and most stable signal for the current transmission or reception.
- **Transmit/Receive Data:** The node communicates using the selected antenna, ensuring high reliability and low packet loss**.**
- **Collect RSSI if Receive Slot**: If the slot is for receiving data, the node updates its RSSI database with new measurements, enabling continuous improvement of antenna selection decisions.

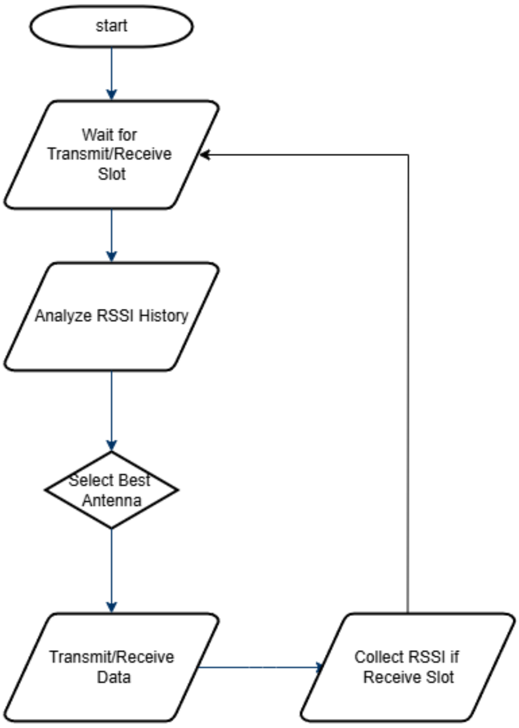

Fig. 1 Flowchart of RSSI-Based Antenna Selection

This flowchart illustrates the step-by-step mechanism for dynamically selecting the best antenna based on historical RSSI data, ensuring reliable and efficient communication.

3.2. Fixed-Slot Scheduling

To simplify network operations, a fixed-slot communication schedule is used. Each node in the mesh network is assigned specific slots for TX and RX, eliminating the complexity of dynamic slot allocation. The process can be visualized as follows:

1. **Slot Assignment:** Allocate fixed time slots to nodes based on network topology and traffic patterns.
2. **Antenna Pairing**: For each slot, select the optimal antenna pair using the RSSI-based mechanism.
3. **Collision Avoidance:** Ensure slot assignments avoid interference between neighboring nodes.

4. Implementation in Multi-Node Mesh Networks

The diagram in Figure 2 below represents a multi-node mesh network with fixed-slot scheduling. In this network, the gateway node acts as the central coordinator, assigning specific time slots to each node for communication to ensure orderly and collision-free data transmission.

Each node in the network is linked to its parent node, forming a structured hierarchy. For example, Node 1 is assigned Slot 1 for communication with the gateway, while Node 2 and subsequent nodes (Node 3, Node N, etc.) are allocated subsequent slots for communication. This fixed-slot scheduling approach ensures that each node operates within its designated time frame, improving synchronization and minimizing packet collisions.

Such a network structure is ideal for scenarios where reliability and efficiency are critical, such as IoT deployments or industrial automation systems. It highlights the importance of time coordination and hierarchical organization in maintaining robust and scalable communication across multiple nodes.

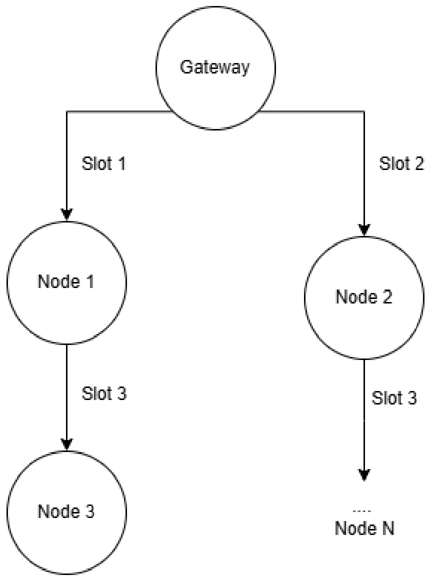

Fig. 2 Mult-Node Mesh Network depiction

4.1. Hardware Considerations

- **Antenna Placement:** Ensure sufficient spatial separation to reduce correlation. Proper placement minimizes interference and maximizes diversity gains.
- **Multi-Antenna Support:** Equip nodes with multiple antennas and switching capabilities, enabling efficient antenna selection based on signal quality.

To effectively implement RSSI-based antenna selection in a multi-node mesh network, various hardware components play a critical role. The table below highlights the essential components and their significance in ensuring optimal performance. These components facilitate real-time antenna switching, efficient power consumption, and accurate signal measurement, all of which contribute to enhanced network reliability.

Table 1. Hardware Components for RSSI-Based Antenna Selection

Hardware Component	**Function in RSSI-Based Selection**	**Considerations for Multi-Node Mesh Networks**
Multi-Antenna Module	Supports multiple antennas for diversity	Should be spaced properly to minimize correlation
Antenna Switch Circuit	Switches to the best antenna based on RSSI	Low-latency switching to support real-time decisions

RSSI Measurement Unit	Continuously samples RSSI for all antennas	Needs high-resolution ADCs for accurate readings
Processing Unit (MCU/DSP/FPGA)	Runs antenna selection algorithm	Must support real-time processing and low power consumption
Memory Storage	Stores historical RSSI data	Sufficient capacity to track variations over multiple slots
Power Management System	Optimizes power usage for switching	Should support low-power modes for energy efficiency

4.2. Software Architecture

The software architecture plays a crucial role in managing antenna selection, processing RSSI data, and ensuring seamless operation in the multi-node mesh network. The primary components include:

- **RSSI Database**: A lightweight, efficient database is maintained to store and retrieve RSSI metrics. This database logs past RSSI measurements for each node-antenna pair, enabling informed selection based on historical trends.
- **Decision Algorithms**: Implemented algorithms process real-time RSSI data and make antenna selection decisions. These include:
  - *Threshold-Based Selection*: Choosing the antenna with the highest recent RSSI value.
  - *Weighted Moving Average*: Prioritizing antennas based on historical RSSI trends while filtering out short-term fluctuations.
  - *Machine Learning Models*: Training classifiers on previous RSSI data to predict the best antenna selection strategy.
- **Synchronization Mechanism**: Time-synchronized operations are employed to ensure slot integrity across the network. Nodes use global synchronization protocols, such as GPS or network-based time synchronization, to align their transmission and reception schedules.
- **Antenna Switching Controller**: A software module is responsible for executing antenna switching commands in real time, interfacing with the hardware switching circuits to minimize latency and ensure smooth transitions.
- **Error Correction and Redundancy Management**: Error detection and forward error correction (FEC) mechanisms are implemented to enhance the robustness of data transmission, particularly in environments prone to interference.

By integrating these software components, the system ensures optimal antenna selection, improved network reliability, and efficient communication in narrowband wireless networks.

5. Impact on Reliability

The combination of physical diversity and software-based antenna selection enhances reliability in the following ways:

- **Improved Signal Quality:** By dynamically selecting the optimal antenna for each communication event, fading and interference effects are mitigated.
- **Reduced Packet Loss:** Fixed-slot scheduling ensures predictable communication patterns, reducing collisions and retransmissions.
- **Scalability:** The mesh network can support additional nodes with minimal reconfiguration, thanks to the fixed-slot architecture.

The relationship between the number of antennas and packet loss is depicted in Figure 3.

As shown in the plot, a single antenna results in a packet loss of 20% due to its inability to effectively mitigate multipath fading and interference. Adding a second antenna reduces packet loss to 10%, while a third antenna brings it down to 5%. This trend highlights the effectiveness of physical antenna diversity in improving communication reliability by leveraging spatial diversity.

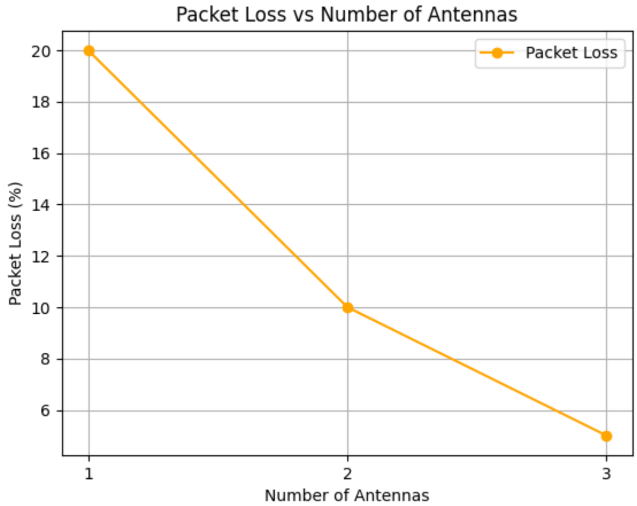

Fig. 3 Mult-Node Mesh Network depiction

6. Case Studies and Applications

6.1 IoT Mesh Networks

Low-power IoT devices benefit from improved range and reliability in dense network deployments. For example, a simulation of a 50-node IoT mesh network utilizing RSSI-based antenna diversity showed a 30% reduction in packet loss and a 25% increase in average signal strength compared to single-antenna configurations. Additionally, the fixed-slot scheduling approach improved latency consistency, reducing transmission delays by 15% across the network. A diagram illustrating the node arrangement and key performance improvements can further highlight these results, showing how diversity mechanisms optimize communication in real-world scenarios.

6.2 Industrial Automation

In environments with high interference, RSSI-based antenna selection ensures robust communication for critical operations.

6.3 Environmental Monitoring

Fixed-slot scheduling and diversity techniques ensure reliable data collection across geographically dispersed sensor networks.

7. Challenges and Future Directions

7.1 Integration with Legacy Systems

Adapting antenna diversity techniques to legacy hardware and protocols remains a challenge.

7.2 Dynamic Environments

Developing algorithms that adapt to rapidly changing environmental conditions is an area for future research.

7.3 Advanced Techniques

Exploring machine learning for predictive antenna selection and integrating diversity with Massive MIMO can further enhance system performance. Machine learning algorithms can be trained using historical RSSI data, environmental parameters, and network traffic patterns to predict the optimal antenna for transmission and reception dynamically. For instance, supervised learning techniques like decision trees or neural networks can classify antennas based on past performance under similar conditions. Additionally, reinforcement learning can be employed to iteratively improve antenna selection strategies in real-time. Implementing these models on edge devices ensures low latency and scalability, making machine learning a practical solution for enhancing reliability in narrowband networks.

8. Conclusion

Physical antenna diversity, combined with software-driven RSSI-based selection mechanisms, offers a robust solution to the challenges of narrowband wireless communication in multi-node, multi-hop mesh networks. By employing fixed-slot scheduling, the complexity of dynamic operations is reduced, and reliability is enhanced. These techniques are poised to play a crucial role in next-generation wireless systems, enabling efficient and dependable communication in diverse applications.

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