Multi-Coil MI Based MAC Protocol for Wireless Sensor Networks

Computer Networks

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Ahmed, N., Zheng, Y. R., & Pommerenke, D. (2013). Multi-Coil MI Based MAC Protocol for Wireless Sensor Networks. Missouri University of Science & Technology.

Introduction

Checkout our Project Implementation: Github

We implemented **Multi-Coil MI Based MAC Protocol** for Wireless Sensor Networks

- Energy-efficient MAC protocol using Magneto-Inductive (MI) communication
- Three-dimensional coil system for directional transmission
- Suitable for both terrestrial and underwater sensor networks

Introduction

Project Methodology:

- Analyzed the research paper to understand the Multi-Coil MI MAC protocol architecture
- Evaluated implementation options and selected NS-3 network simulator due to hardware constraints
- Developed the simulation in NS-3.46, implementing the MAC protocol algorithm and comparing it with CSMA/CA

Understanding the Paper

Challenges in Wireless Sensor Network MAC Protocols:

- **Energy Wastage**
  - Idle listening: nodes continuously monitor the channel
  - Packet collision: simultaneous transmissions waste power
  - Packet overhearing: receiving packets not intended for the node
  - Control packet overhead: excessive handshaking increases energy consumption
- **Underwater Communication Limitations**
  - Slow propagation speed in acoustic communication
  - High path loss and multipath fading
  - Low data rates and high processing power requirements
  - Dynamic channel conditions and signal attenuation

Understanding the Paper

How the Paper Addresses These Challenges

- **Three-Coil System for Omnidirectional Communication**
  - Uses three orthogonal coils (X, Y, Z) to overcome directional limitations
  - All three coils listen simultaneously, but only one transmits at a time
  - REV packet sent three times (once per coil) to find optimal orientation
  - Automatically selects coil pair with strongest RSSI for communication
- **Five-State Energy-Efficient State Machine**
  - **Idle**: Ultra-low power mode (50 μA) - only receiver IC active
  - **Receive**: Packet decoding (200 μA)
  - **Channel Sensing**: Carrier detection before transmission (200 μA)
  - **Data Acquire**: Sensor data collection (250 μA)
  - **Transmit**: Packet transmission (1.12 mA)
- **Component-Level Power Management**
  - Individual control of microcontroller, receiver, transmitter, and sensors
  - Components turned OFF when not needed to minimize energy wastage

Understanding the Paper

How the Paper Addresses These Challenges

- **Efficient Packet Structure**
  - **REV (13 bytes)**: Handshake with coil information for optimal pairing
  - **ACK (5 bytes)**: Minimal acknowledgment with selected coil pair
  - **DATA (3-19 bytes)**: Variable length reduces control overhead
  - Each packet includes target ID matching to avoid unnecessary processing
- **Collision Avoidance Mechanisms**
  - Carrier sensing before transmission to detect channel availability
  - Directional nature of MI coils reduces interference range
  - Spatial reuse: different coil pairs allow concurrent transmissions
- **Magneto-Inductive Communication Advantages**
  - Works effectively in both terrestrial and underwater environments
  - Stable channel response without multipath fading issues
  - Magnetic permeability of soil/water similar to air
  - Lower propagation delays compared to acoustic communication

Algorithm Discussed in the Paper / Methodology

Packet Types and Structure:

Carrier	Preamble	Target ID	Packet ID	Tx ID	Tx Coil ID	EOF
1 byte	1 byte	4 bytes	1 byte	4 bytes	1 byte	1 byte

Reservation Packet

Carrier	Packet ID	Tx Coil ID	Rx Coil ID	EOF
1 byte	1 byte	1 byte	1 byte	1 byte

Acknowledgment

Carrier	Packet ID	Data Packets	EOF
1 byte	1 byte	1 byte – 16 bytes	1 byte

Data Packet

Algorithm Discussed in the Paper / Methodology

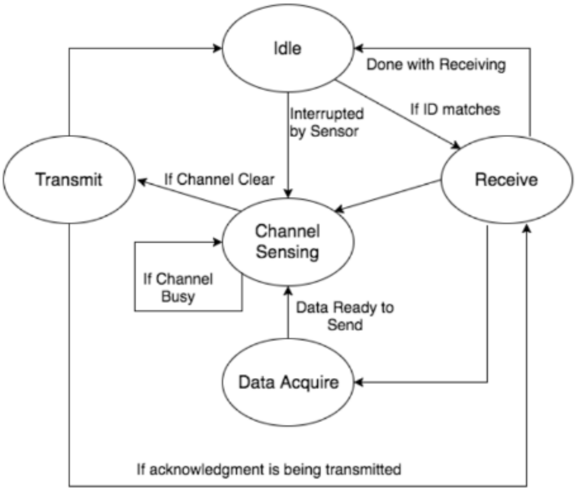
Five-State Machine with Component-Level Power Management:

TABLE III
ACTIVE AND IN-ACTIVE COMPONENTS IN EACH STATE

Working Mode	**Components**	**Power Mode**
Idle State	Micro-controller	Sleep
	Receiver Circuitry	ON
	Transmit Circuitry	OFF
	Sensors	OFF
Receive State	Micro-controller	ON
	Receiver Circuitry	ON
	Transmit Circuitry	OFF
	Sensors	OFF
Data Acquire State	Micro-controller	ON
	Receiver Circuitry	OFF
	Transmit Circuitry	OFF
	Sensors	ON
Channel Sensing State	Micro-controller	ON
	Receiver Circuitry	ON
	Transmit Circuitry	OFF
	Sensors	OFF
Transmit State	Micro-controller	ON
	Receiver Circuitry	OFF
	Transmit Circuitry	ON
	Sensors	OFF

Algorithm Discussed in the Paper / Methodology

State Transition Diagram:



Algorithm Discussed in the Paper / Methodology

Phase 1: Communication Initiation

- All nodes start in **Idle State** (50 μA) - listening on all three coils simultaneously
- When data is available, node transitions to **Data Acquire State** - collects sensor readings
- Node moves to **Channel Sensing State** - checks if channel is busy or clear
- If clear, enters **Transmit State** and sends **REV packet three times**
- Each REV (13 bytes) transmitted once per coil: X, Y, then Z
- REV contains: Target ID + Packet Type + Transmit Coil Information
- Three transmissions ensure at least one coil pair has strong signal, regardless of node orientation

Algorithm Discussed in the Paper / Methodology

Phase 2: Optimal Coil Pair Selection

- Destination node receives all three REV packets on its three coils
- Transitions to **Receive State** and compares RSSI values of all three receptions
- Selects coil pair with strongest signal strength (e.g., X-to-Z or Y-to-Y)
- Performs **Channel Sensing** and enters **Transmit State**
- Sends back compact **ACK packet (5 bytes)** using the selected best coil
- ACK contains: Packet Type + Selected TX Coil ID + Selected RX Coil ID
- Source receives ACK in **Receive State** - both nodes now know optimal coil pair

Algorithm Discussed in the Paper / Methodology

Phase 3: Data Transmission & Spatial Reuse

- Source performs channel sensing again, then sends **Data packet**
- Data packet (3-19 bytes) transmitted using pre-selected optimal coil
- Destination receives in **Receive State**, decodes packet, validates Target ID
- Both nodes return to **Idle State** after successful transmission
- Complete sequence: REV $\rightarrow$ ACK $\rightarrow$ DATA with minimal energy expenditure
- **Spatial Reuse**: Different node pairs can use different coils simultaneously
- Example: Node A-B communicate via Coil X while Node C-D use Coil Y concurrently
- Directional MI communication enables interference-free parallel transmissions

Implementation

What is Network Simulator 3 (NS-3)?

- Open-source discrete-event network simulator for research and education
- Widely used for simulating internet protocols, wireless networks, and MAC layers
- Written in C++ with Python bindings for scripting
- Provides detailed network stack simulation: applications, transport, network, MAC, and physical layers
- Key Features:
  - Supports WiFi, LTE, sensor networks, and custom protocol development
  - Real-time packet transmission, state management, and energy tracking
  - Built-in tools for performance metrics: latency, throughput, packet delivery
  - NetAnim support for network visualization
- **Why NS-3 for our project?**
  - Robust MAC protocol implementation framework
  - No hardware required - pure software simulation
  - Validated and trusted by research community

Implementation

mi-mac-demo.cc: Basic Protocol Demonstration

- **Purpose**: Demonstrate complete Multi-Coil MI MAC protocol workflow
- **Key Components Implemented**:
  - Three packet type enumerations: REV, ACK, DATA
  - Three coil IDs: X, Y, Z (orthogonal coils)
  - Five-state machine: Idle, Receive, Channel Sensing, Data Acquire, Transmit
- **Core Functions**:
  - `CalculateRSSI()`: Simulates signal strength for each coil (-45.5, -52.3, -48.7 dBm)
  - `SelectBestCoil()`: Compares RSSI values and selects strongest coil
  - `StateTransition()`: Tracks and displays state machine transitions
  - `SendPacket()`: Simulates packet transmission with structure details
- **Workflow Simulated**:
  - Source sends REV packet 3 times (once per coil)
  - Destination receives, selects best coil via RSSI comparison
  - ACK sent back using selected coil
  - DATA packet transmitted using established coil pair

Implementation

mi-mac-comparison.cc: Performance Comparison with CSMA/CA

- **Purpose**: Compare Multi-Coil MI MAC with traditional CSMA/CA protocol
- **Enhanced Features**:
  - `EnergyMetrics` structure: Tracks current consumption per state (Table II values)
  - Calculates total energy, packet count, and state transitions
  - Implements both MI MAC and CSMA/CA protocols for side-by-side comparison
- **CSMA/CA Implementation**:
  - RTS (Request to Send) → CTS (Clear to Send) → DATA → ACK handshake
  - Four packets vs. three packets in MI MAC (REV → ACK → DATA) for single communication pair.
  - Higher control overhead and energy consumption
- **Comparison Output**:
  - Side-by-side table: packets sent, state transitions, total energy
  - Energy savings percentage calculation
  - Key advantages: spatial reuse, directional communication, lower overhead
  - Validates paper's energy efficiency claims using actual current values

Results

Performance Comparison: Multi-Coil MI MAC vs CSMA/CA

Metric	Multi-Coil MI	CSMA/CA
Total Packets Sent	5	4
State Transitions	12	13
Total Energy (μJ)	11,183.84	14,058.40

Energy Savings: 20.4%

Results

Protocol Overhead Analysis:

- **Multi-Coil MI MAC**: REV ($3\times$) $+$ ACK $+$ DATA $=$ 5 packets total
- **CSMA/CA**: RTS $+$ CTS $+$ DATA $+$ ACK $=$ 4 packets total

- Despite sending more packets, MI MAC is more energy-efficient
- Reason: Optimized coil selection reduces retransmissions
- Lower power states used effectively
- Directional communication reduces interference

Results

Validation of Paper's Claims:

- Energy consumption matches Table II values:
  - Idle: 50 μA, Receive: 200 μA, Data Acquire: 250 μA
  - Channel Sensing: 200 μA, Transmit: 1120 μA
- State machine operates as designed (Figure 3)
- Packet structures match specifications (Figure 4)
- RSSI-based coil selection improves link quality
- Three-coil system ensures reliable communication

Results

Demonstrated Advantages of Multi-Coil MI MAC:

- **Energy Efficiency**: 20.4% savings over CSMA/CA
- **Spatial Reuse**: Different node pairs use different coils concurrently
- **Directional Communication**: RSSI-based selection optimizes links
- **Collision Avoidance**: Channel sensing + coil diversity
- **Lower Overhead**: Optimized handshake vs RTS/CTS
- **Dual Environment**: Works in terrestrial and underwater networks

Results

Simulation Effectiveness:

- NS-3 successfully simulated MAC protocol without hardware
- Complete protocol workflow demonstrated
- State machine behavior verified
- Energy metrics tracked accurately
- Performance comparison achieved
- Paper's theoretical advantages validated through simulation

Limitations & Future Work

Current Limitations:

- **Short Communication Range**: MI communication limited to 40-50 meters due to magnetic field attenuation
- **Coil Misalignment**: Significant signal degradation when coils are severely misaligned despite 3D coil system
- **Simulation-Only**: No hardware prototype implementation - results based on software simulation

Future Work:

- Hardware prototyping with actual MI coils and sensor nodes
- Multi-hop routing protocol for extended network coverage
- Adaptive power control to optimize range vs. energy trade-off
- Real-world testing in underwater and underground environments
- Integration with LoRa or other long-range technologies for hybrid networks

THANK YOU

Questions?

GitHub: https://github.com/NishitVSP/-Multi-Coil-MI-Based-MAC-Protocol-for-Wireless-Sensor-Networks