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Spatial Reusability-Aware Routing Protocols for End-to-End Throughput Optimization in Multi-Hop Wireless Networks

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ABSTRACT:

Multi-hop wireless networks rely on efficient routing mechanisms to achieve high end-to-end throughput while operating under shared-spectrum and interference constraints. Conventional routing protocols primarily focus on metrics such as hop count, link quality, or transmission delay, often overlooking the impact of spatial channel reuse on network-wide performance. This paper proposes a Spatial Reusability-Aware Routing Protocol (SRARP) that incorporates interference relationships, transmission ranges, and concurrent transmission opportunities into route selection. The proposed approach evaluates candidate paths based on their ability to maximize spatial reuse while minimizing harmful interference among neighboring links. A throughput-oriented routing metric is developed by jointly considering link capacity, interference levels, hop count, and the potential for simultaneous transmissions. By selecting routes that enable greater spatial separation between active transmissions, the protocol aims to improve end-to-end throughput and spectrum utilization without significantly increasing routing overhead. The performance of the proposed protocol is evaluated through simulation under varying network densities, traffic loads, and interference conditions. Results demonstrate that spatial-reusability-aware routing can provide improved end-to-end throughput and more efficient channel utilization compared with conventional shortest-path and interference-unaware routing approaches.

Keywords: Multi-Hop Wireless Networks, Spatial Reuse, Interference-Aware Routing, End-to-End Throughput Optimization, Routing Protocols, Wireless Network Optimization, Spectrum Utilization, Concurrent Transmissions, Link Scheduling, Interference Management, Channel Capacity, Network Performance.

1. INTRODUCTION

Due to the shared, broadcast nature of wireless communication media and lossy channel conditions, selecting routes that maximize end-to-end throughput is a fundamental challenge in multi-hop wireless networks. Over the past decade, a wide variety of routing protocols have been engineered to overcome link loss and routing inefficiency.

However, a critical limitation in existing wireless routing metrics—such as Expected Transmission Count (ETX) and Expected Transmission Time (ETT)—is their reliance on minimizing the total transmission count or latency required to deliver a single packet. While this strategy reduces individual packet overhead, it fails to optimize total network throughput when concurrent transmissions occur.

The core distinction between wired and wireless networks lies in spatial reusability. Wireless signals attenuate over distance according to signal propagation loss models. Consequently, two links separated by sufficient distance can transmit simultaneously on the same frequency channel without causing destructive interference.

Traditional metrics avoid concurrently active areas by routing packets around bottlenecks in a single line, neglecting opportunities where parallel concurrent links could operate simultaneously. This paper therefore explicitly accounts for spatial reusability during path selection.

We introduce two practical routing frameworks: Spatial Reusability-Aware Single-Path Routing (SASR) and Spatial Reusability-Aware Anypath Routing (SAAR). Our contributions are summarized as follows:

- We quantify the throughput loss incurred by traditional link-quality metrics that ignore spectrum spatial reuse.
- We formulate single-path route selection under spatial contention as a Binary Integer Programming (BIP) optimization problem and develop the SASR algorithm.
- We extend spatial reusability modeling to opportunistic anypath routing (SAAR), designing candidate selection and forwarding-list mechanisms.

2. EXISTING SYSTEM & DRAWBACKS

Conventional multi-hop wireless routing protocols rely heavily on link-quality-aware routing metrics. For single-path routing, metrics like ETX, EATX, ETT, and WCETT measure individual link delivery ratios and bandwidth to construct minimum-cost paths. Similarly, modern anypath (opportunistic) routing protocols such as ExOR and MORE leverage the broadcast nature of wireless media, allowing any neighbor that overhears a packet to participate in forwarding.

Disadvantages of Existing Systems

- Spatial Unawareness: Ignores channel reusability; selects bottleneck paths where consecutive hops severely contend for medium access.
- Suboptimal Throughput: Minimizing total transmissions for a single packet does not translate to maximizing continuous-flow throughput.
- Centralized MAC Overhead: Existing spatial scheduling solutions require strict MAC-layer time synchronization and centralized control.

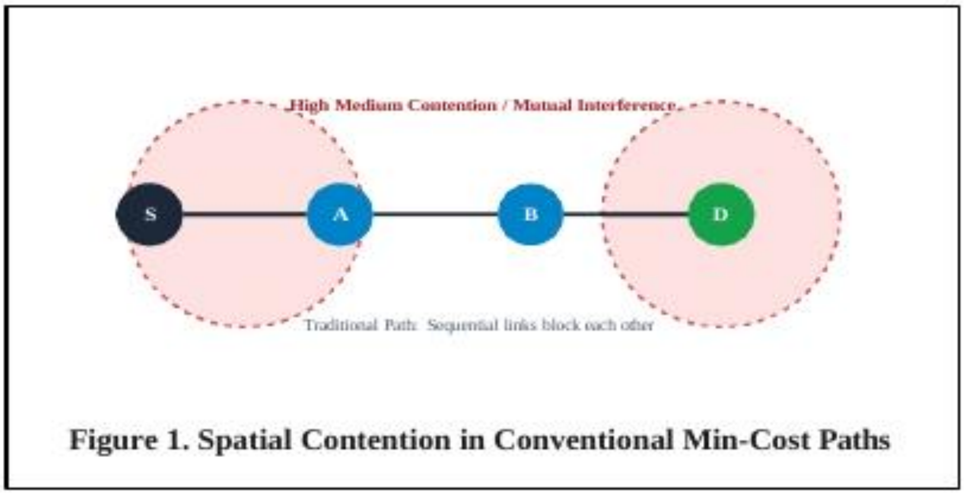

Figure 1. Spatial Contention in Conventional Min-Cost Paths

3. PROPOSED SYSTEM ARCHITECTURE

To address the limitations of existing metrics, we propose a spatial reusability-aware routing framework. By integrating physical-layer signal attenuation modeling into route generation, the protocols favor topologies with high spatial independence, allowing parallel pipeline transmissions.
The system architecture comprises four unified operational blocks: topology and interference sensing, spatial reusability analysis, a dual spatial-routing engine containing SASR and SAAR, and the forwarding and MAC interface.

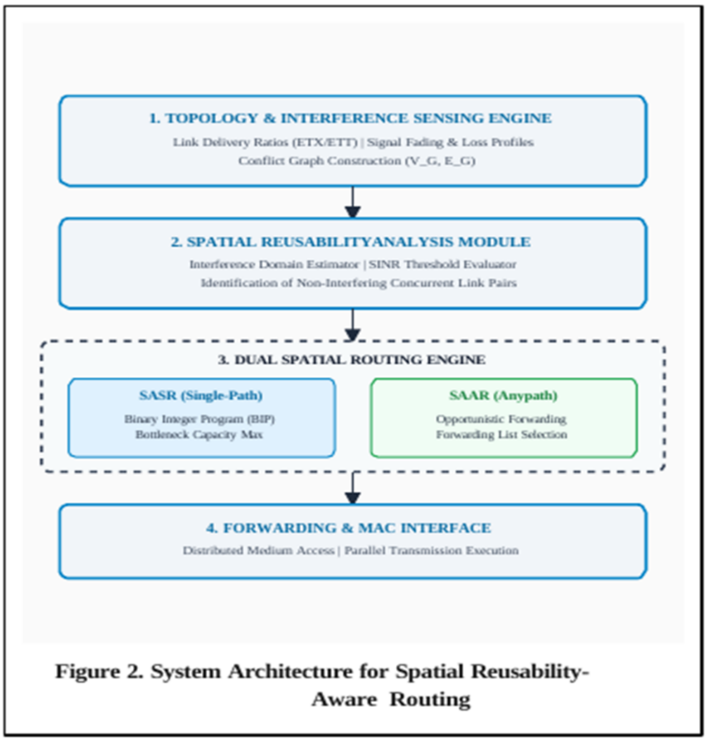

Figure 2. System Architecture for Spatial Reusability-Aware Routing

4. SYSTEM MODULES

The proposed implementation is organized into two primary operational modules alongside supporting topology sensing components:

Module 1: Spatial Single-Path Routing (SASR)

The SASR module identifies a single primary path that minimizes mutual interference between active links along the path. Given a wireless network modeled as a directed graph G = (V, E) and a corresponding conflict graph C_G, route selection is formulated as a Binary Integer Program (BIP):
Maximize: Capacity(P) = min(e ∈ P) { r_e / (1 + Σ(e' ∈ I(e)) x_e') }
where x_e ∈ {0,1} represents link inclusion, r_e is the link transmission rate, and I(e) denotes the set of links contending with link e in the conflict graph. SASR calculates path costs using a distributed gradient algorithm.

Module 2: Spatial Anypath Routing (SAAR)

The SAAR module extends reusability to opportunistic multi-path scenarios. Instead of a strict single route, SAAR assigns a candidate forwarding set F_i to each intermediate node i.
When node i transmits a packet, any node j ∈ F_i that successfully overhears the packet participates in forwarding based on a pre-calculated priority order. SAAR computes the spatial cost of forwarding candidates by evaluating both loss probabilities and the spatial overlap of candidate transmission domains.

Advantages of the Proposed System

- Significant Throughput Gains: Achieves up to 2.9x gain for single-path routing and up to 62.7x gain for opportunistic anypath routing.
- No Centralized MAC Scheduling: Runs on top of standard distributed 802.11 MAC protocols without requiring tight time synchronization.
- Conflict-Graph Awareness: Formulates real physical interference into binary integer constraints, eliminating path self-interference.

5. PROTOCOL PERFORMANCE COMPARISON

SASR and SAAR are compared against conventional ETX, ETT, and ExOR routing protocols across various network densities. Evaluation results confirm that spatial awareness yields substantial throughput benefits, especially under high network densities where concurrent spatial links are abundant.

Routing Protocol	Routing Type	Median Gain	Peak Gain
ETX / ETT	Single-Path	1.0x (Baseline)	1.0x
SASR (Proposed)	Single-Path	1.6x (60%)	2.9x
ExOR / MORE	Anypath	1.0x (Baseline)	1.0x
SAAR (Proposed)	Anypath	1.13x (13.2%)	62.7x

Table 1. Performance comparison of conventional and proposed routing protocols.

6. SYSTEM CONFIGURATION

The algorithms and simulation environment were developed using the NS-2 simulator with standard hardware and software prerequisites.

Hardware Requirements

- Processor: Intel Pentium IV or higher (1.1 GHz minimum)
- System Memory (RAM): 256 MB minimum (512 MB recommended)
- Hard Disk Storage: 20 GB available disk space
- Peripherals: Standard Keyboard and Mouse

Software Requirements

- Operating System: Windows XP / Linux (Ubuntu 12.04 LTS / Fedora)
- Simulation Framework: Network Simulator 2 (NS-2.35)
- Programming Languages: C++ (Core Protocol Engine), OTcl (Simulation Scripts), JAVA (GUI Analysis)

7. CONCLUSION

In this paper, we have demonstrated that carefully incorporating spatial reusability into routing decisions can enhance end-to-end throughput in multi-hop wireless networks. We proposed two routing protocols: SASR for single-path routing and SAAR for opportunistic anypath routing. By using conflict graphs and spatial interference modeling, the protocols select routes that facilitate parallel, non-interfering packet transmissions. The reported simulations demonstrate throughput improvements of up to 2.9x for single-path routing and up to 62.7x for anypath routing over the stated baseline metrics, with minimal control overhead.

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