

Medium-Access Control Protocols for Heterogeneous Mobile Ad Hoc Networks with Directional Antennas

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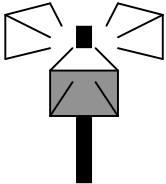
**NATO Workshop on Cross-Layer Issues in the
Design of Tactical Mobile Ad Hoc Wireless
Networks**

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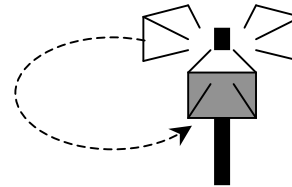
Directional Antennas in Mobile Ad Hoc Networks

- Great performance benefits if directional antennas utilized effectively in mobile ad hoc networks
 - Directional antennas can result in high complexity
 - Adaptive beam-forming, management of beam pointing
 - Complex neighbor discovery, need for location information
 - Our focus: fixed-beam antenna subsystems exploited with relatively simple protocols/algorithms
 - Multiple fixed-beam directional antennas at node
- 
- together give node **omni-directional coverage** in azimuth
 - **separate transceiver** for each beam
 - number of beams may differ for different nodes

- Characteristics of node with multiple fixed beams/transceivers
 - Cost is multiple transceivers rather than signal processing
 - No management of beam-pointing by protocols required
 - No beam switching at transceiver front end is required
 - Neighbor discovery same as with omni-directional antennas
 - No explicit location information required
- Necessary/desirable properties of MAC protocol
 - MAC management of transceivers is consistent with physical-layer constraints of antenna subsystems
 - MAC mitigates unique performance limitations arising due to physical-layer characteristics of antenna subsystems
 - Same MAC supports nodes with any number of beams

Relationship Between Physical-Layer Characteristics and MAC-Layer Design

- Multiple antenna subsystems at node result in **co-site interference** among transceivers

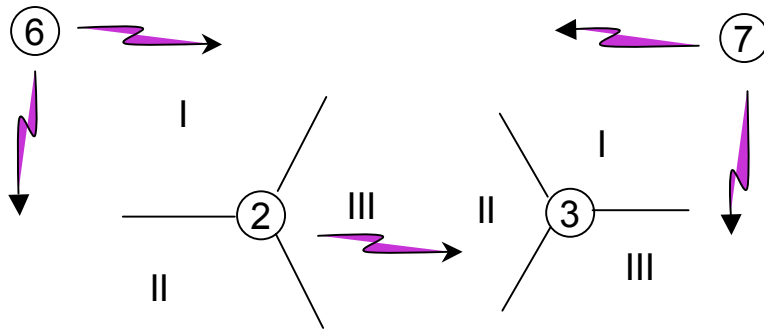


- Signal energy from one transceiver coupled into another transceiver through antennas, other EMI mechanisms
- Possible MAC-layer solutions:
 - no TX at node when RX expected by any transceiver at node
 - TX limited only based on characteristics of antenna subsystems
- Use of directional antennas exacerbates the **receiver blocking problem** in packet radio network
 - MAC-layer solution must address this problem for best performance

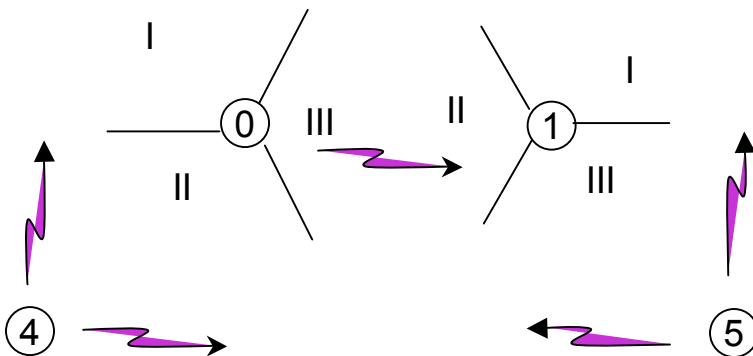
System Design

- Characteristics of nodes in network
 - Node with omni-directional antenna has one half-duplex transceiver
 - Node with multiple beams has one half-duplex transceiver per beam
 - Collision-avoidance (RTS-CTS) random-access MAC protocol
 - Direct-sequence spread-spectrum packet transmission
- “Baseline” MAC protocol addresses co-site interference problem
 - Multiple frequency channels:
 - One control channel for RTS, CTS packets
 - One or more traffic channels for DATA, ACK packets
 - Intercepted CTS blocks local use of a frequency channel in beam (mitigates hidden-terminal problem)
 - Exponential back-off algorithm (response to perceived busy terminal)
 - Single MAC layer controls transceivers of all beams at a node
 - Expected packet reception at any beam’s transceiver blocks all transmissions at node

Example of Eight-Node Network

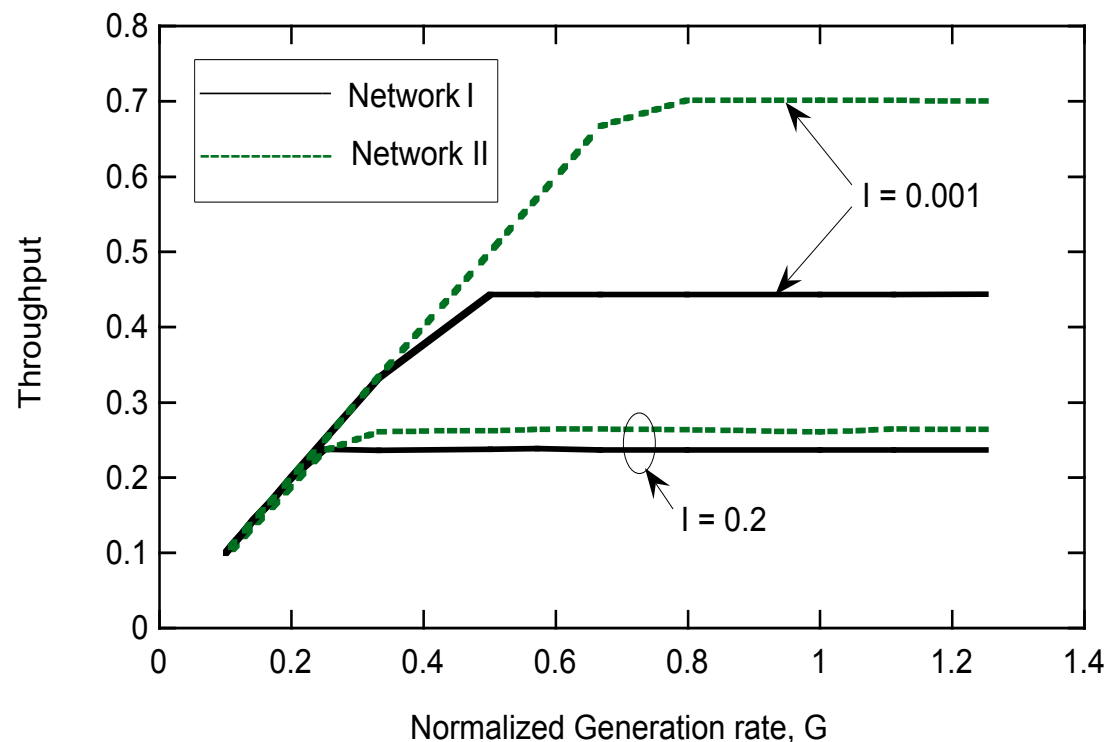


- Two frequency channels
- Two scenarios considered
 - Network I: All nodes have omni-directional antennas
 - Network II: Nodes 0-3 have three 120-degree beams each
- Beam orientation in network II isolates active 0-1 link from active 2-3 link
- Poisson traffic at each node
 - Node 0 to node 1: rate G
 - Node 2 to node 3: rate G
 - Nodes 4-7 to adjacent corners: rate $1/2$
- Performance measure
 - Link-layer throughput, no routing
 - Throughput per node for 0 and 2



Performance with Baseline MAC Protocol

- Directional antennas reduce MAI on links of interest
- With no interfering traffic, expect doubling of throughput with directional antennas
 - Anticipated doubling is observed
- With heavy interfering traffic, expect greater benefit from directional antennas
 - **Opposite** phenomenon is observed



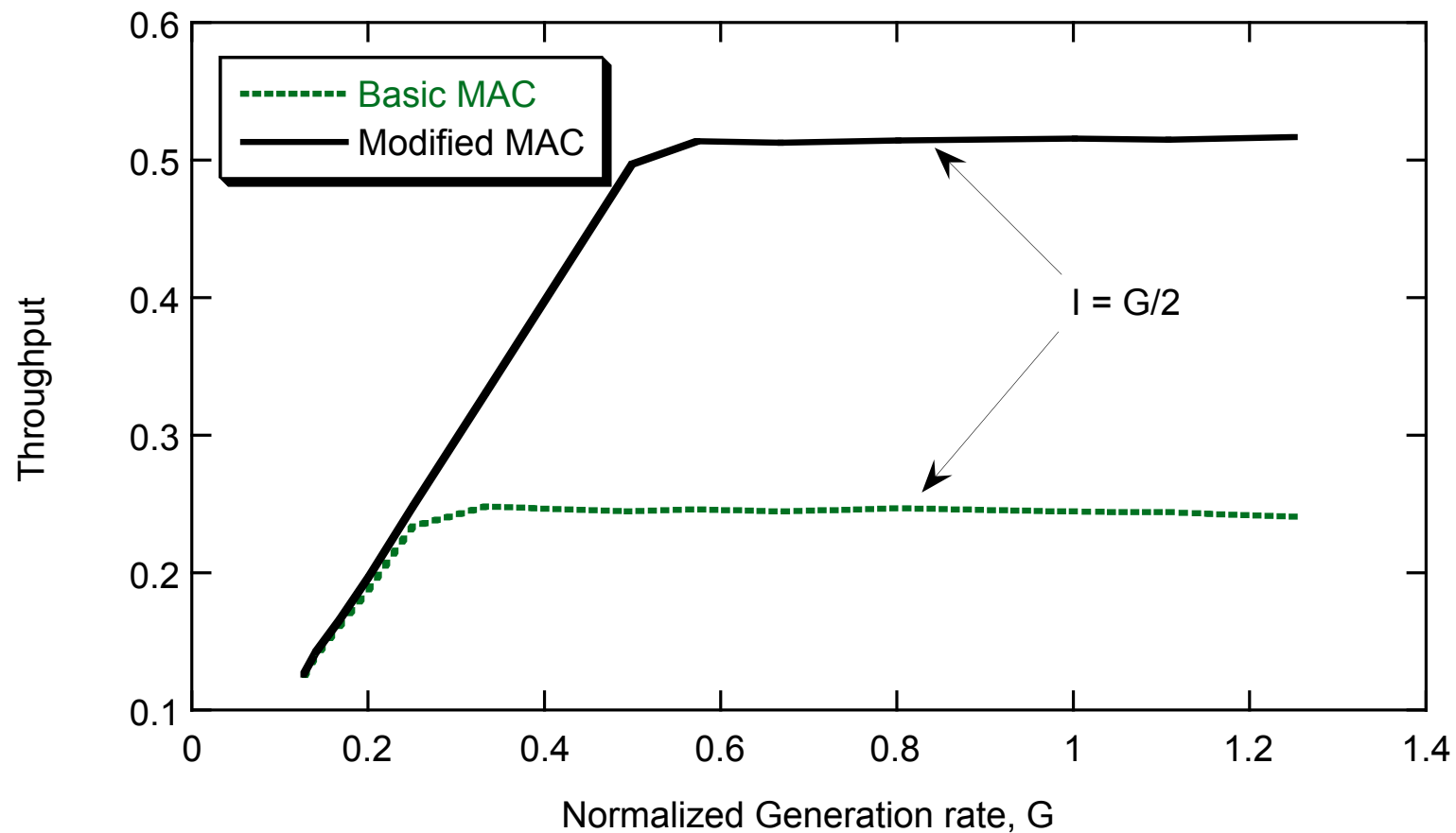
Performance with Baseline MAC Protocol

- Throughput more sensitive to interfering traffic if nodes 0-3 employ directional antennas
 - Introduction of directional antennas actually *decreases* throughput in this network if interfering traffic is heavy
- Phenomenon is a manifestation of the **receiver blocking problem**
 - Transmitter of RTS erroneously infers “busy radio” from missing CTS, initiates back-off algorithm
 - Problem also arises with omni-directional antennas
 - Random placement of interferer more likely to cause problem for node with directional antenna than with omni antenna
 - So problem has greater impact on performance if some nodes employ directional antennas

A Simple Solution: the negative CTS

- A node with all local traffic channels blocked for a beam can still transmit on control channel
- Transmitter can be more aggressive in retransmission attempts if intended receiver has blocked channels than if it is busy
- Modified MAC protocol
 - Transmitter still employs original back-off algorithm in response to missing CTS
 - Receiver with all traffic channels blocked responses to RTS with negative CTS (NCTS) containing information about channel availability
 - Transmitter exploits NCTS information to determine aggressiveness of retransmission algorithm
 - Algorithm accounts for information in recent NCTS packets
- Modified MAC protocol improves performance with both directional antennas and omni-directional antennas
 - Greater improvement occurs for network employing some nodes with multiple directional antennas

Performance with Modified MAC Protocol



More than two-fold increase in throughput under heavy-traffic conditions

Conclusions

- Properly designed MAC protocol mitigates co-site interference at node with multiple fixed-beam antennas
- Packet radio network including nodes with directional antennas is more vulnerable to receiver-blocking problem than network with only omni-directional antennas
- Alternative collision-avoidance MAC protocol mitigates receiver blocking by using negative CTS control packet
 - Improves performance of network with only omni antennas
 - Provides greater improvement if some nodes have directional antennas

Reference

- A. Swaminathan, D. L. Noneaker, and H. B. Russell, "The Receiver Blocking Problem in a DS Mobile Ad Hoc Network with Directional Antennas," to appear in the *Proceedings of the 2004 IEEE Military Communications Conference* (Monterey, CA), Nov. 2004.