Wireless & Optical Communication Conference (WOCC2008)

Exploiting Multi-Dimensional Diversity in Distributed Resource Management for Mobile Ad-hoc Networks

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April 24, 2008

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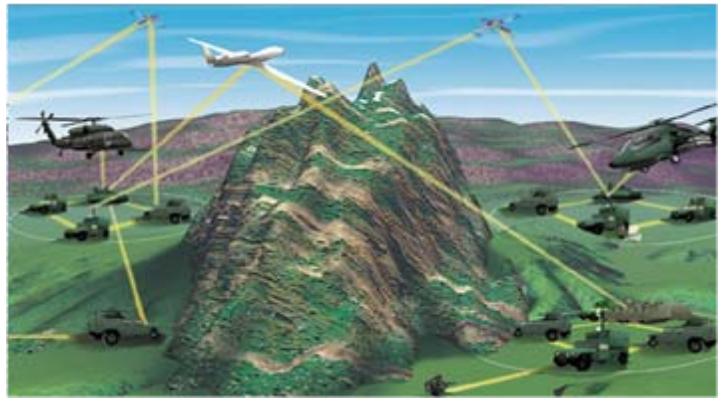
Outline

- Motivation and Background
- Challenges and Our Research Focus
- System Model
- Distributed CSMA/CA Medium Access Control with Multi-Dimensional Diversity
- Performance Analysis
- Conclusion

Background and Motivation

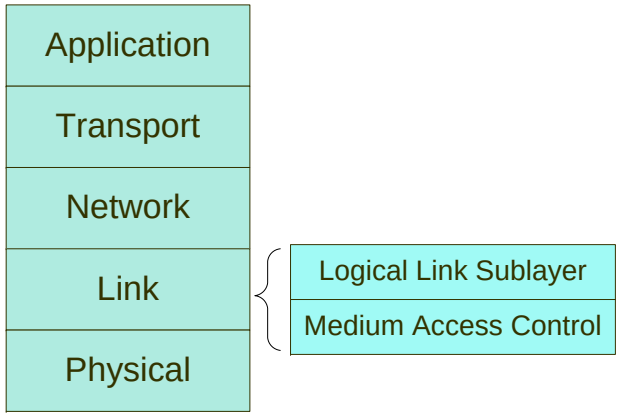
- **Mobile Ad-Hoc Network (MANET)**
  - An autonomous system consisting of mobile nodes connected by wireless links
  - Main characteristics
    - Random movement and arbitrary organization of the nodes -- Rapid and unpredictable change in ***topology and connectivity***
    - Each node in a MANET acts as a router, forwarding data packets to other nodes - *a* ***decentralized network***
    - Data packets may reach destination via multiple relaying nodes -- ***multi-hop transmission***
  - Widespread research activities in MANET
    - Topology and mobility control
    - Network protocol design across all layers
    - System level design and deployment
    - Variety of applications in both commercial and military sectors



A key technology for tactical edge systems

Medium Access Control (MAC)

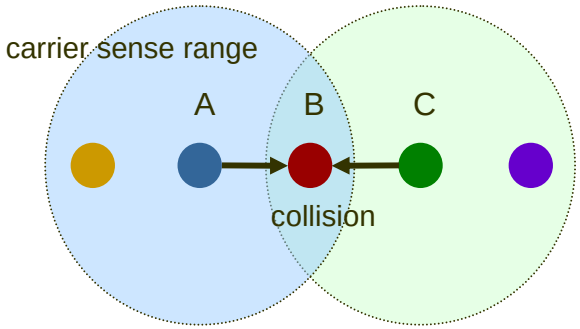
- **MAC is part of the link layer protocol**
  - Specify the rules by which a frame is transmitted onto the link
  - Coordinate the frame transmissions of many nodes sharing a broadcast link – multiple access control
- **Other link and MAC layer functions**
  - Error control, power control, transmission format selection
- **Significance in MANET**
  - Achievable system capacity and performance highly depends on MAC protocol design
- **Typical MAC protocols**
  - Channel partitioning protocols: FDMA, TDMA, CDMA
  - Random access protocols: ALOHA, Slotted ALOHA, CSMA
  - Taking-Turns protocols: polling, token-passing
- **Carrier Sense Multiple Access (CSMA): listen before speaking**
  - With collision detection: CSMA/CD, used in Ethernet
  - With collision avoidance: CSMA/CA, used in 802.11 WLAN



The Internet Protocol Stack

Challenges and Our Research Focus (1)

- **Key challenge: Designing radio resource management in a *distributed* network**
  - Without a fixed infrastructure in traditional wireless networks, control and management of MANET have to be distributed across all nodes
  - Distributed radio resource management is a much more challenging problem than a centralized approach
  - Main issues
    - Hidden terminal problem
    - Exposed terminal problem
    - Deafness problem
    - Throughput degradation in multi-hop transmission



Challenges and Our Research Focus (2)

- Focus of our research: multi-channel and multi-interface MAC design
  - Threshold based medium access control to explore multi-dimensional diversity
  - Distributed medium-adaptive scheduling algorithm to provide QoS applications
  - Joint channel assignment and routing algorithm design
  - Secure multi-path routing to improve robustness and resilence

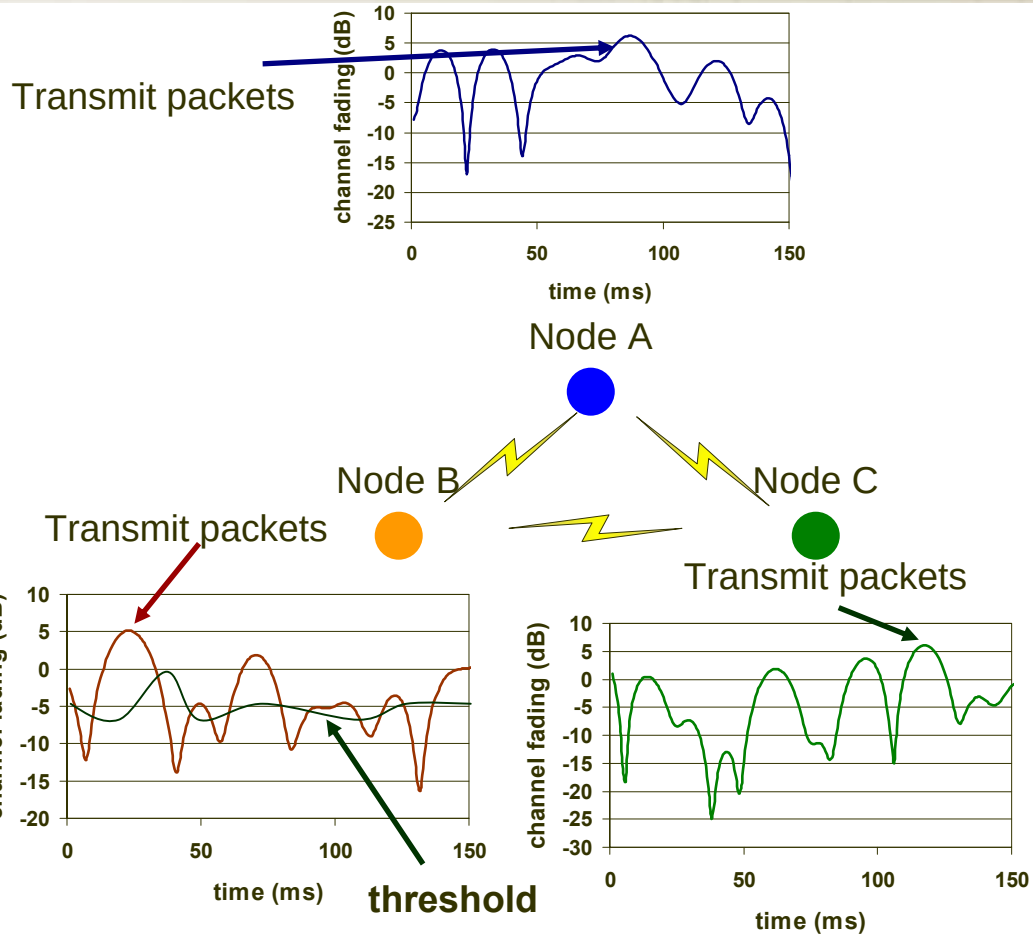
Multi-Channel Multi-Interface MAC Design

- Assumptions
  - There are total of N channels available in the spectrum
  - Each node is equipped with M radio interfaces, and $M \leq N$
  - Each interface is capable of switching to one of the N channels with a switching delay δs
- Exploiting diversity gain in multi-dimensions
  - *Frequency diversity*
  - *Time diversity*
  - *User diversity*
  - Spatial diversity

Exploiting Diversity in Distributed MAC

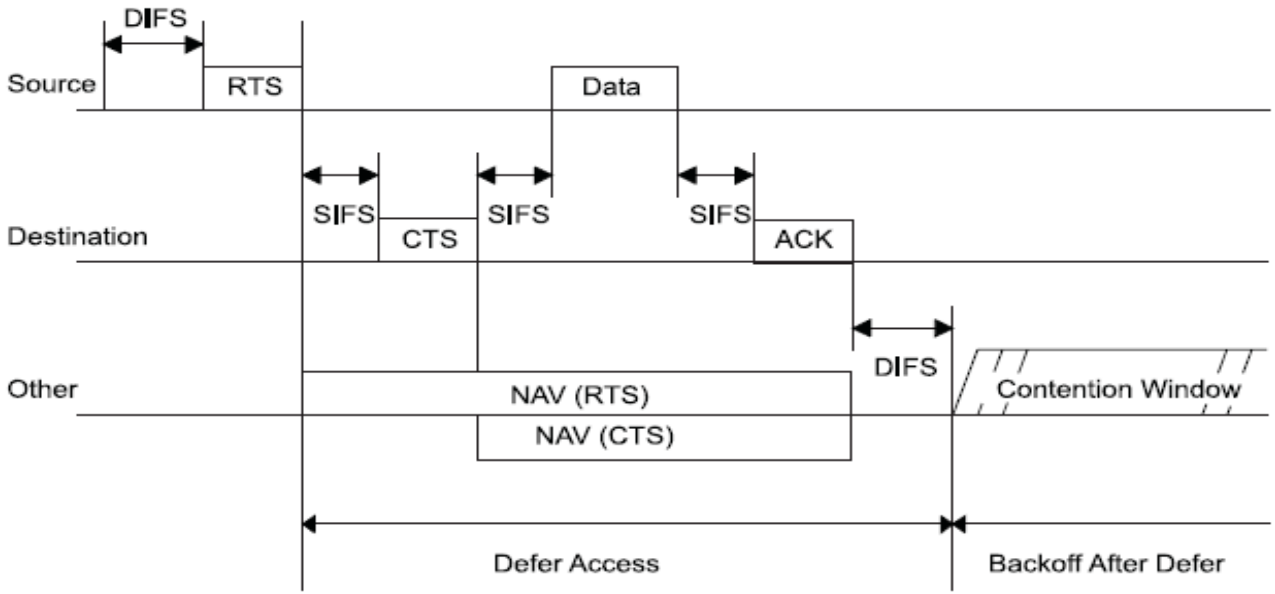
- **Key idea: threshold based medium access control**
  - A node accesses the medium when its channel state is good
    - Channel estimation and prediction
    - Threshold adaptation

Outcome: coordinated transmission via distributed/localized operation



System Model

- Mobile ad-hoc system architecture
  - No centralized entity controlling the medium access and transmission
  - Each mobile node acts as a router
  - A data packet may reach its destination through multiple relaying nodes, i.e., multi-hop transmission
- CSMA/CA MAC protocol as the basis of our design
  - RTS/CTS handshake option



Source: IEEE 802.11

Distributed CSMA/CA MAC Protocol (1)

- Channel estimation and transmission rate selection
  - Receiver based estimation based on the received SINR of a frame
- Adaptive threshold based medium contention
  - A mobile node sends a RTS frame to the receiving node for channel reservation
  - Upon receiving a CTS frame with the indicated transmission rate, the mobile node compares it with a threshold
    - If it is above the threshold, the mobile node sends the data frame. Otherwise, it aborts the transmission and waits for the next contention opportunity

Distributed CSMA/CA MAC Protocol (2)

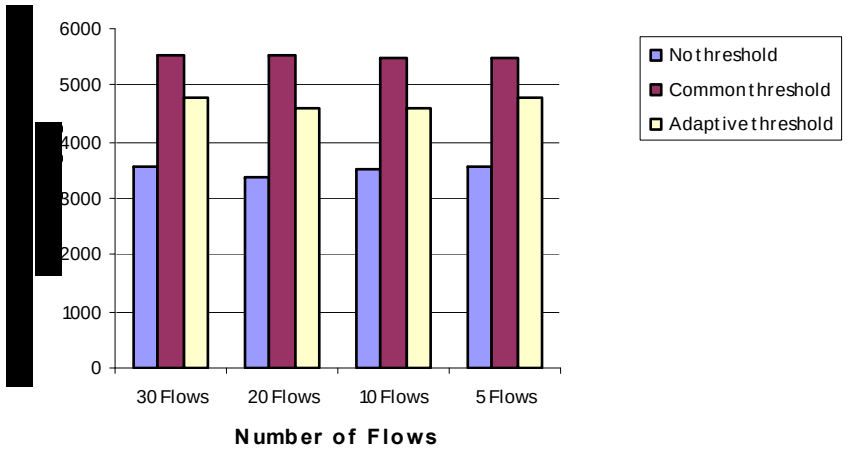
- **Methods for threshold setting**
  - **A common threshold for all the nodes**
    - maximize the throughput, but lack of fairness among heterogeneous nodes
  - **Adaptive threshold at each node**
    - Improve the throughput and also achieve fairness

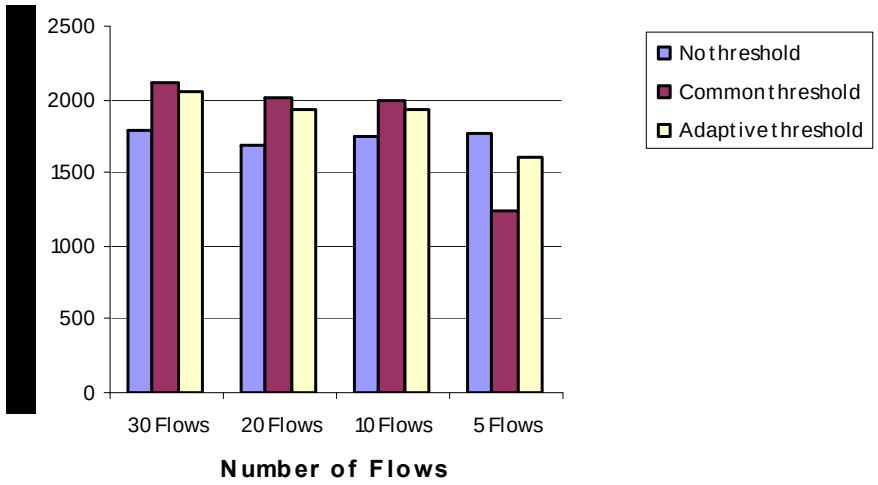
$$T_{new}^{j} = \rho \cdot \left(\alpha R^{j} + (1-\alpha) T_{old}^{j} \right) \quad \alpha, \rho \in [0,1]$$

- **Channel probing and estimation overhead**
  - **Critical in tracking the time varying RF channel**
  - **Introduce additional overhead in a distributed system**
  - **This overhead will hamper the diversity gain and cost the system throughput eventually**
  - **Careful design to achieve the best tradeoff**

Performance Analysis and Evaluation (1)

- **Network simulation results**
  - **Average transmission rate has an increase between 35% - 60%, with good RF conditions of the nodes.**
  - **The gain comes from time and user diversity**
  - **The quantitative results are limited by the current rate sets in 802.11b. Further improvement can be achieved with advanced PHY design**
  - **The aggregate throughput increase is hampered by the additional overhead of RTS/CTS handshake**





Performance Analysis and Evaluation (2)

- **Theoretical analysis**
  - **Average throughput with a threshold**

$$C_t = \int_1^{\infty} f(n)dn \int_{R_t}^{\infty} f(r_t)dr_t \int_0^{\infty} f(T_i)dT_i \cdot \frac{B}{\sum_{i=1}^{n} T_i + B/r_t},$$

where n: number of contensions; T_i: contension duration;

B: MAC packet size; r_t: transmission rate; R_t: rate threshold

The pdf $f(\cdot)$ of r.v., n, T_i, and r_t, can be obtained and used to calculate the throughput per node C_t

  - **Existing 802.11 MAC design has a poor efficiency, i.e., ~ 40 – 50% of the link capacity**
    - **This further hampers the potential diversity gain if using the existing timing and synchronization structure**

Performance Analysis and Evaluation (3)

- **Experimentation and Research Testbed Development**
  - **Objective:**
    - **Demonstrate and validate the designed protocols/algorithms in realistic operating conditions**
    - **Provide a close-to-reality testing environment to facilitate technology transition**
    - **Gain experiences in developing and implementing a research testbed to facilitate wireless networking research**
  - **Technical Approach**
    - **A laboratory emulator/field trial network testbed**
    - **A set of static and mobile 802.11x radio nodes**
    - **Each node can be equipped with different radio interfaces**
      - 802.11a/b/g, GNU radio, Zigbee
    - **Dynamic configuration of the topology of the connections of the nodes**
    - **The protocols at different layers can be designed and emulated**
      - PHY: designed via the GNU radio interface
      - MAC: designed via the driver API
      - Networking: designed via LINUX kernel
      - Application: implemented at the PC node itself

Conclusion

- Distributed radio resource management for MANET
- Adaptive threshold based MAC protocol to exploit time and user diversity
- Other work on joint channel assignment and routing algorithm design, secure multipath routing
- The performance improvement highly depends on the network topology and link variation in MANET
- The achievable diversity gain in MANET is expected to be smaller than the gain in a centralized network
- Providing robustness and efficiency improvement in MANET remains a challenging task