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

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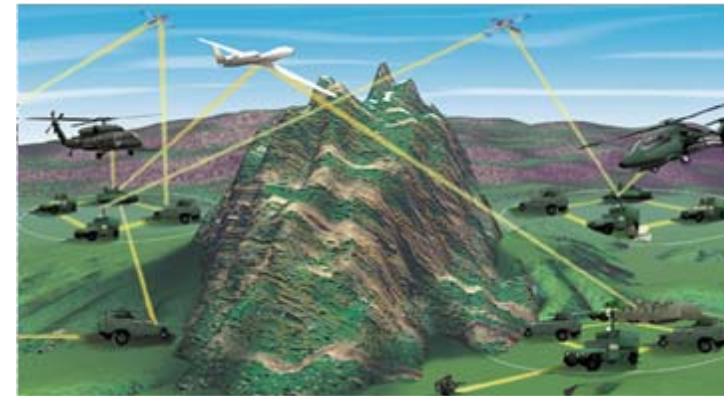
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Outline

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

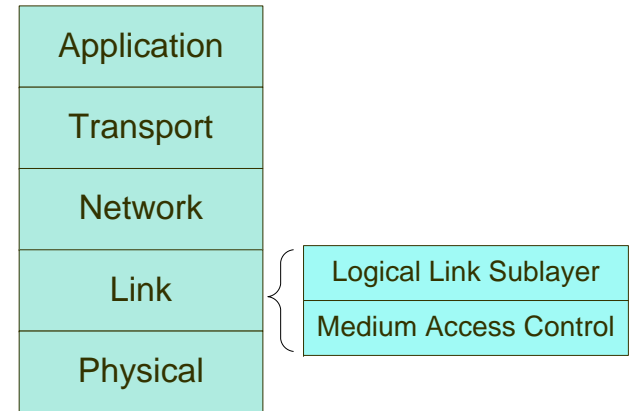
- **Mobile Ad-Hoc Network (MANET)**
 - An autonomous system consisting of mobile nodes connected by wireless links
 - Main characteristics
 - Random movement and arbitrary organization of the nodes -- Rapid and unpredictable change in **topology and connectivity**
 - Each node in a MANET acts as a router, 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)

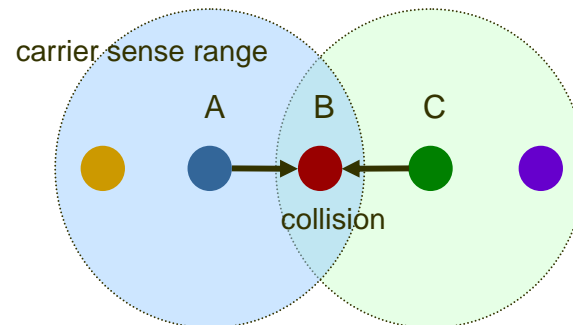
- **MAC is part of the link layer protocol**
 - Specify the rules by which a frame is transmitted onto the link
 - Coordinate the frame transmissions of many nodes sharing a broadcast link – multiple access control
- **Other link and MAC layer functions**
 - Error control, power control, transmission 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 resilience**
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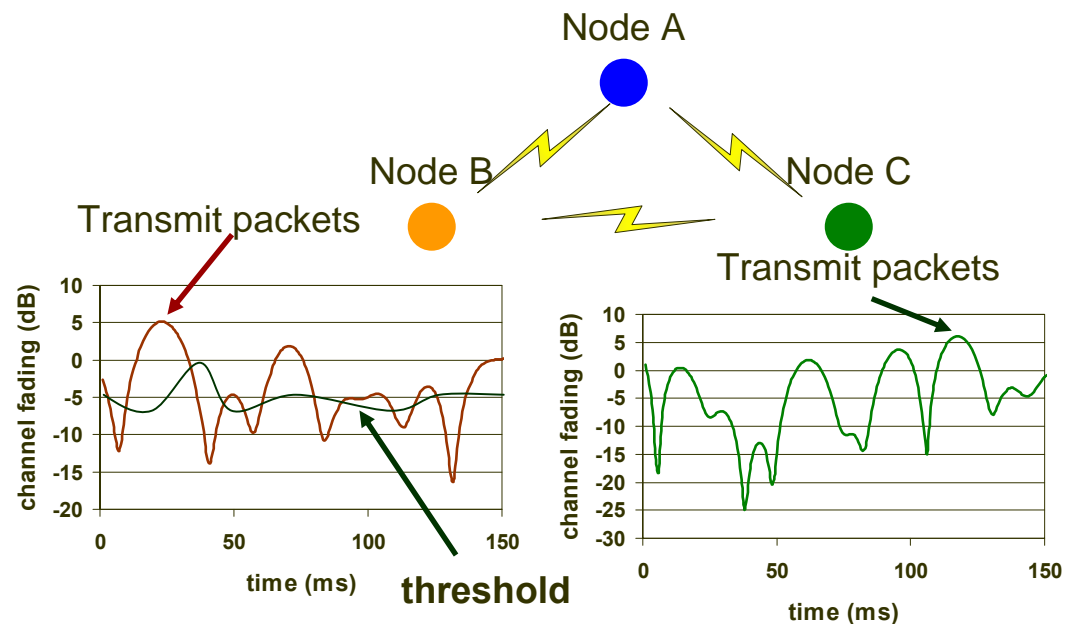
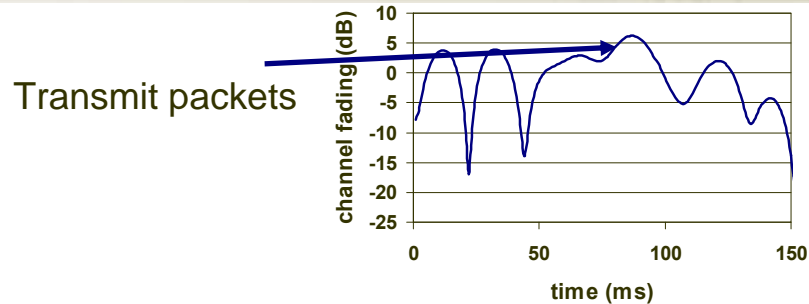
Multi-Channel Multi-Interface MAC Design

- **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 δ_s
 - **Exploiting diversity gain in multi-dimensions**
 - *Frequency diversity*
 - *Time diversity*
 - *User diversity*
 - **Spatial diversity**
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Exploiting Diversity in Distributed MAC

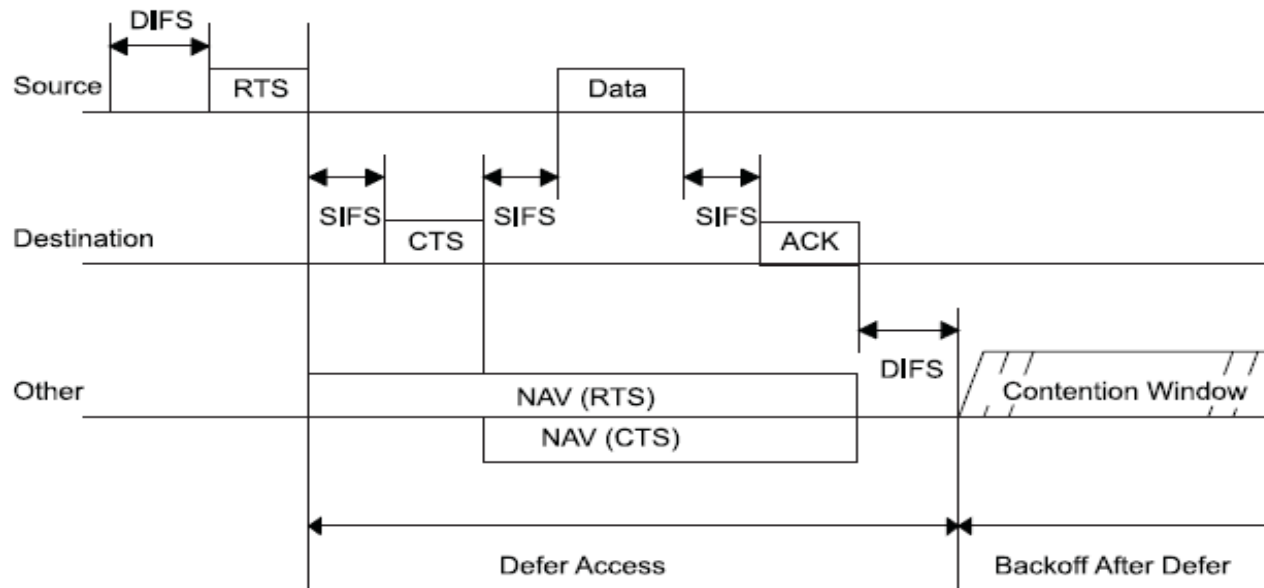
- **Key idea: threshold based medium access control**
 - A node accesses the medium when its channel state is good
 - Channel estimation and prediction
 - Threshold adaptation

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



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**
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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

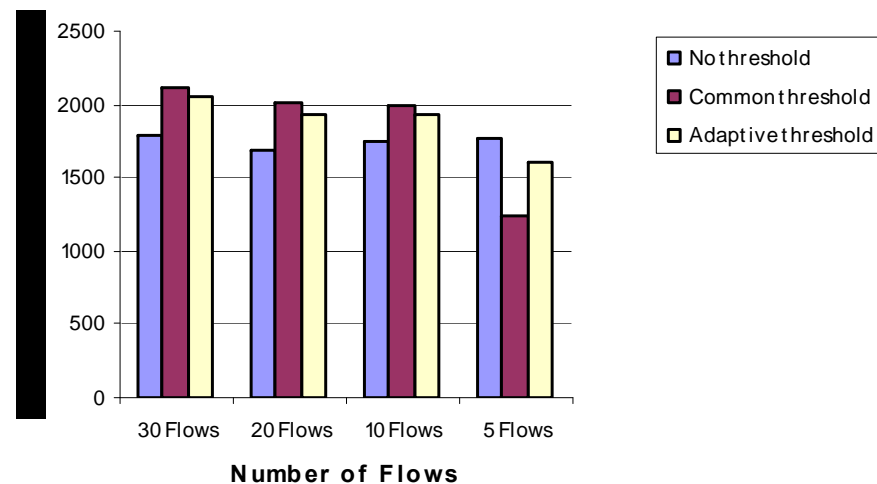
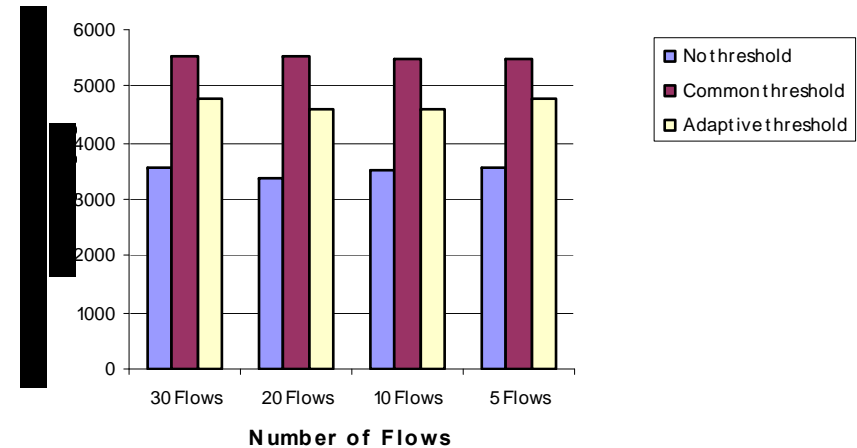
$$T_{new}^j = \rho \cdot \left(\alpha R^j + (1 - \alpha) T_{old}^j \right) \quad \alpha, \rho \in [0, 1]$$

- **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**
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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**
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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
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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**
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