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

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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 resilience
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 $\delta_s$
- 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

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

- 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

\[
C_t = \int_1^\infty f(n)dn \int_{R_i}^\infty f(r_i)dr_i \int_0^\infty f(T_i)dT_i \cdot \frac{B}{\sum_{i=1}^{n}T_i + B/r_i},
\]

where \(n\): number of contensions; \(T_i\): contention duration; 
\(B\): MAC packet size; \(r_i\): transmission rate; \(R_i\): rate threshold

The pdf \(f(\cdot)\) of r.v., \(n, T_i,\) and \(r_i\), 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