CMPE 257: Wireless Networking

SET MAC-2:

Medium Access Control Protocols
NAMA Improvements

- Inefficient activation in certain scenarios.
  - For example, only one node, $a$, can be activated according NAMA, although several other opportunities exist.

---

We want to activate $g$ and $d$ as well.
Node + Link (Hybrid) Activation

- Additional assumption
  - Radio transceiver is capable of code division channelization (DSSS — direct sequence spread spectrum)
  - Code set is $C$.

- Code assignment for each node is per time slot:
  \[ i \cdot \text{code} = i \cdot \text{prio mod } |C| \]
Hybrid Activation Multiple Access (HAMA)

- Node state classification per time slot according to their priorities.
  - Receiver (Rx): intermediate prio among one-hop neighbors.
  - Drain (DRx): lowest prio amongst one-hop.
  - BTx: highest prio among two-hop.
  - UTx: highest prio among one-hop.
  - DTx: highest prio among the one-hop of a drain.
HAMA (cont.)

Transmission schedules:

- **BTx** —> all one-hop neighbors.
- **UTx** —> selected one-hops, which are in Rx state, and the **UTx** has the highest prio among the one-hop neighbors of the receiver.
- **DTx** —> Drains (DRx), and the **DTx** has the highest prio among the one-hops of the DRx.
Suppose no conflict in code assignment.

Nodal states are denoted beside each node:
- Node D converted from Rx to DTx.
- Benefit: one-activation in NAMA to four possible activations in HAMA.
Other Channel Access Protocols

- Other protocols using omni-directional antennas:
  - LAMA: Link Activation Multiple Access
  - PAMA: Pair-wise Activation Multiple Access

- Protocols that work when uni-directional links exist.
  - Node A can receive node B’s transmission but B cannot receive A’s.

- Protocols using direct antenna systems.
Comparison of Channel Access Probability

$p=0.0001$ Node/Square Area

![Graph showing comparison of channel access probability](image)

- NAMA
- HAMA
- PAMA
- LAMA

Channel Access Probability

Transmission Range
Protocol Throughput Comparison

Data Packet Size=100

Data Packet Size=10

Throughput S

Channel Access Probability p'

Throughput S

Channel Access Probability p'

Legend:
- CSMA (N=3)
- CSMA (N=10)
- CSMA/CA (N=3)
- CSMA/CA (N=10)
- HAMA (N=3)
- HAMA (N=10)
- NAMA (N=3)
- NAMA (N=10)
Comments

- Scheduled-access protocols are evaluated in static environments and what about their performance in mobile networks?
- Neighbor protocol will also have impact on the performance of these protocols
- Need comprehensive comparison of contention-based and scheduled access protocols.
References


References

MAC Protocols Using Directional Antennas

- Basic protocols
- Directional Virtual Carrier Sensing (DVCS)
- Directional MAC (D-MAC) in UDAAN
MAC Protocols Using Directional Antennas

- The MAC protocols so far assume that a node’s transmissions reach all of its neighbors.
- With powerful antenna systems, it is possible to limit transmissions and receptions to desired directions only.
- This can increase spatial reuse and reduce interferences to neighbors nodes.
- Caveat:
  - Not all neighbor nodes defer access.
  - Directional receiving is not always desired.
Omni-Directional and Directional Transmissions

Omni-directional transmission

Directional transmission
Directional Antenna Models

- Antenna systems
  - Switched beam – fixed orientation
  - Adaptive beam forming – any direction

- Simulation models:
  - Complete signal attenuation outside the directional transmission beamwidth ($\theta$)
  - “Cone plus ball” model

- Directional transmissions have higher gains
  - Possible to use power control to reduce the gain

- Various medium access control schemes have been proposed and/or investigated (see Refs).
Basic Scheme One

OTOR (omni-transmit, omni-receive)
- The usual omni RTS/CTS based collision avoidance
- All packets are transmitted and received omni-directionally.
- IEEE 802.11 MAC protocol uses such scheme.

DEFER ACCESS

**Diagram:**
- **SRC**:
  - RTS
  - SIFS
  - CTS
  - DATA
  - SIFS
  - ACK
  - NAV(RTS)
- **DEST**
  - NAV(CTS)
- **OTHER**
  - NAV(RTS)
  - NAV(CTS)

DIFS
**Basic Scheme Two**

- **DTOR (directional-transmit, omni-receive)**
  - Packets are transmitted directionally.
  - Packets are received omni-directionally.
  - Increased spatial reuse (+) and collisions (-).

```
GROUP 1
  E  B  A

GROUP 2
  D  C  G
```

- Talks btw. A & B, C & D can go on concurrently;
- – More collisions may occur;
- + Spatial reuse is increased;
- + Nodes spend less time waiting.
Basic Scheme Three

- DTDR (directional-transmit, directional-receive)
  - All packets are transmitted and received directionally.
  - Aggressive spatial reuse

- Talks btw. A & B, C & D can go on concurrently;
- – More collisions may occur;
- – Channel status info. is incomplete;
- + Aggressive spatial reuse;
- + Nodes spend less time waiting.
Basic Scheme Four

- MTDR (mixed transmit, directional receive)
  - CTS packets are transmitted omni-directionally while other packets are transmitted directionally.
  - Tradeoff between spatial reuse and collision avoidance

- Diagram:
  - GROUP 1:
    - E
    - B
    - A
    - F
  - GROUP 2:
    - D
    - C
    - G

- Details:
  - \( D \) sends RTS to \( C \) directionally;
  - \( C \) replies with omni-CTS;
  - \( A \) and \( G \) defer their access and won’t cause collisions;
  - However, \( A \) cannot talk with \( B \) at the same time.
Predictions from the Analysis [WG03]

- The DTDR scheme performs the best among the schemes analyzed.
  - Increased spatial reuse and reduced interference through directional transmissions.
  - Directional receiving cancels much interferences from neighbors and hidden terminals.

- Throughput of the DTDR scheme with narrow beamwidth has a slightly increase when $N$ increases.
  - Spatial reuse effect is more conspicuous.
  - Scalability problem is mitigated.
Simulation Results [WG03]

- Higher-gain directional transmissions have negative effects on throughput and delay.
  - More nodes are affected.

- Influence of side lobes can be almost canceled out if:
  - The level of side lobes is reasonably low through the advancement of antenna systems.
  - Carrier sensing threshold is raised such that nodes are less sensitive to channel activities.
Advanced Schemes

- Directional Virtual Carrier Sensing ([TMRB02])
  - Angle-of-Arrival (AoA) information available
  - Nodes record direction information and defer only to non-free directions (directional NAV)

- UDAAN ([RRSWP05])
  - Switched beam antenna
  - Experimental system was built to test the effectiveness of directional antenna systems
Details on Directional NAV

- Physical carrier sensing still omni-directional
- Virtual carrier sensing be directional – directional NAV
  - When RTS/CTS received from a particular direction, record the direction of arrival and duration of proposed transfer
  - Channel assumed to be busy in the direction from which RTS/CTS received
Directional NAV (DNAV)

- Nodes overhearing RTS or CTS set up directional NAV (DNAV) for that Direction of Arrival (DoA)
Directional NAV (DNAV)

- Nodes overhearing RTS or CTS set up directional NAV (DNAV) for that Direction of Arrival (DoA)
Directional NAV (DNAV)

- New transmission initiated only if direction of transmission does not overlap with DNAV, i.e., if \(( > 0 )\)
D-MAC

- Forced Idle is to avoid starvation
- FI-Busy "aggressive"
- Tight integration with power control
Directional Neighbor Discovery

- Three kinds of links (neighbors)
  - N-BF, without beam forming
  - T-BF, using only transmit-only beamforming
  - TR-BF, using transmit and receive beamforming

- Two methods for discovery
  - Informed discovery
  - Blind discovery
Directional Packet Transmission

D-O transmission

B's omni receive range

D-D transmission

B's directional receive beam
Related topics

- Neighbor protocol and topology management
- Energy efficiency
- Routing
References

Acknowledgments

- Parts of the presentation are adapted from the following sources:
  - Prasant Mohapatra, UC Davis,
    http://www.cs.ucdavis.edu/~prasant/ECS257/NOTES/Ad
MAC Protocols for Networks with Multiple Channels

- Motivation and issues
- Summary of approaches
- Examples
- Open research problems
Motivation for Using Multiple Channels

- Multiple *orthogonal* channels available in IEEE 802.11
  - 3 channels in 802.11b
  - 12 channels in 802.11a
- Multiple channels available in general
- Utilizing multiple channels can improve throughput and reduce delays
  - Allow simultaneous transmissions in the same 2-hop neighborhood.

![Diagram showing single channel and multiple channels](attachment://diagram.png)
Issues with Multiple Channels

- Senders and receivers need to “meet” in one of many channels
- Hidden and exposed terminals are now problems involving more than one channel
  - Similar problems than with space division
- Each node may have one or multiple radios
- Half duplex nodes, even with multiple radios per node:
  - At best, a node can receive or transmit over one or multiple radios, but not both
- Synchronization is hard to avoid w/o a dedicated control channel.
Approaches*

1. **Dedicated Control Channel**
   - Dedicated control radio & channel for all control messages
   - DCA[Wu2000], DCA-PC[Tseng2001], DPC[Hung2002].

2. **Split Phase**
   - Fixed periods divided into (i) channel negotiation phase on default channel & (ii) data transfer phase on negotiated channels
   - MMAC[J.So2003], MAP [Chen et al.]

3. **Common Hopping**
   - All non-busy nodes follow a common, well-known channel hopping sequence -- the control channel changes.
   - HRMA[Tang & JJ 98], CHMA, CHAT, RICH [Tzamaloukas & JJ]

4. **Parallel Rendezvous**
   - Each node publishes its own channel hopping schedule
   - SSCH [Bahl04], McMAC [So et al]

* Mo, So and Walrand, “Comparison of Multi-Channel MAC Protocols,” MSWIM 05.
Approach 1: Dedicated Control Channel

Dedicated control radio and control channel
DCA[Wu2000], DCA-PC[Tseng2001], DPC[Hung2002].

3. [Control Chan]:
   S ---- RTS (Suggested Data Chan.) --> R

4. [Control Chan]:
   S <-- CTS (Agreed Data Chan.) ---- R

5. [Control Chan]: (optional)
   S --- Reservation (broadcast) ---> All

6. [Data Chan]:
   Sender --- Data Packet ---> Receiver
Dedicated Control Channel

Rendezvous & contention occur on the control channel.

Legend: Node 1   Node 2   Note 3   Node 4

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Nasipuri’s Protocol

- Assumes N transceivers per host
  - Capable of listening to all channels simultaneously
- Sender searches for an idle channel and transmits on the channel [Nasipuri99WCNC]
- Extensions: channel selection based on channel condition on the receiver side [Nasipuri00VTC]
- Disadvantage: High hardware cost (today!)*

* In the future (~5 to 10 years), having 4 radios per node will be affordable
Approach 2: Split-Phase

- Time is divided into (equal) **periods**.
- Each period consists of 2 phases: **control** (channel negotiation), **data** transfer.
- Examples are: MIMAC [J. So 2003] (UIUC), MAP [Chen 2003]
- Channel negotiation happens on a **default channel**. Nodes negotiate the channels to use.
- RTS/CTS/Data on the separate channels
Split-Phase

Channel negotiation on a common channel

Time

Channel

Ch2

Ch1

Ch0

Hello (1,2,3) (1)

Rsv (1)

Hello (2,3) ...

Control Phase

Data Transfer Phase

Legend: Node 1  Node 2  Note 3  Node 4
MMAC (So and Vaidya)

Assumptions

- Each node is equipped with a single transceiver
- The transceiver is capable of switching channels
- Channel switching delay is approximately 250us
  - Per-packet switching not recommended
  - Occasional channel switching not too expensive
- Multi-hop synchronization is achieved by other means
MMAC

- Idea similar to IEEE 802.11 PSM
  - Divide time into beacon intervals
  - At the beginning of each beacon interval, all nodes must listen to a predefined common channel for a fixed duration of time (ATIM window)
  - Nodes negotiate channels using ATIM messages
  - Nodes switch to selected channels after ATIM window for the rest of the beacon interval
Preferred Channel List (PCL)

- Each node maintains PCL
  - Records usage of channels inside the transmission range
  - High preference (HIGH)
    - Already selected for the current beacon interval
  - Medium preference (MID)
    - No other vicinity node has selected this channel
  - Low preference (LOW)
    - This channel has been chosen by vicinity nodes
    - Count number of nodes that selected this channel to break ties
Channel Negotiation

- In ATIM window, sender transmits **ATIM** to the receiver
- Sender includes its PCL in the ATIM packet
- Receiver selects a channel based on sender’s PCL and its own PCL
  - Order of preference: HIGH > MID > LOW
  - Tie breaker: Receiver’s PCL has higher priority
  - For “LOW” channels: channels with smaller count have higher priority
- Receiver sends **ATIM-ACK** to sender including the selected channel
- Sender sends **ATIM-RES** to notify its neighbors of the selected channel
Channel Negotiation

Common Channel  

Selected Channel

A  

B  

C  

D  

ATIM Window  

Beacon Interval

Time  

Beacon
Channel Negotiation

Common Channel

Selected Channel

ATIM Window

Beacon Interval

ATIM - ACK(1)

ATIM - RES(1)
Channel Negotiation

Common Channel

Selected Channel

A

ATIM

ATIM-RES(1)

B

ATIM-ACK(1)

C

ATIM-ACK(2)

D

ATIM

ATIM-RES(2)

ATIM Window

Beacon Interval

Time

Beacon

ATIM Window

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Channel Negotiation

Common Channel

Selected Channel

A

ATIM

ATIM-RES(1)

Beacon

Channel 1

B

ATIM-ACK(1)

CTS

ACK

Channel 1

C

ATIM-ACK(2)

CTS

ACK

Channel 2

D

ATIM

ATIM-RES(2)

CTS

ACK

Channel 2

Time

ATIM Window

Beacon Interval
Simulation Model

- ns-2 simulator
- Transmission rate: 2Mbps
- Transmission range: 250m
- Traffic type: Constant Bit Rate (CBR)
- Beacon interval: 100ms
- Packet size: 512 bytes
- ATIM window size: 20ms
- Default number of channels: 3 channels
- Compared protocols
  - 802.11: IEEE 802.11 single channel protocol
  - DCA: Wu’s protocol
  - MMAC: Proposed protocol
Wireless LAN - Throughput

MMAC shows higher throughput than DCA and 802.11

Aggregate Throughput, 15 Flows

- 802.11
- DCA
- MMAC

Aggregate Throughput, 32 Flows

- 802.11
- DCA
- MMAC

Packet arrival rate per flow (packets/sec)

30 nodes

64 nodes

Packet arrival rate per flow (packets/sec)
Multi-hop Network – Throughput

Aggregate Throughput, 40 Flows, 3 Channels

- **802.11**
- **DCA**
- **MMAC**

Aggregate Throughput, 40 Flows, 4 Channels

- **802.11**
- **DCA**
- **MMAC**

Packet arrival rate per flow (packets/sec)

3 channels

4 channels
Throughput of DCA and MMAC
(Wireless LAN)

M/MAC shows higher throughput compared to DCA
Analysis of Results

- **DCA**
  - Bandwidth of control channel significantly affects performance
  - Narrow control channel: High collision and congestion of control packets
  - Wide control channel: Waste of bandwidth
  - It is difficult to adapt control channel bandwidth dynamically

- **MMAC**
  - ATIM window size significantly affects performance
  - ATIM/ATIM-ACK/ATIM-RES exchanged once per flow per beacon interval — reduced overhead
    - Compared to packet-by-packet control packet exchange in DCA
  - ATIM window size can be adapted to traffic load
Further Work Needed

- Dynamic adaptation of ATIM window size based on traffic load for MMAC
- Efficient multi-hop clock synchronization
- Better uses of data segment
- Multipoint communication support
Approach 3: Common Hopping

All *idle* nodes follow the *same* channel hopping sequence.

E.g., HRMA[Tang98], CHMA[Tzamaloukas2000], CHAT[Tzamaloukas2000]

3. [Common Channel]: S ---- RTS ---> R
4. [Next Common Channel]: everyone else [Same Channel]: S <-- CTS ---- R
5. [Same Channel]: S ---- Data ---> R

All return to “Current Common Channel” after sending/receiving
3. Common Hopping

Idle nodes hop together in “common channel”

Legend: Node a  Node b  Note c  Node d

Enough for one RTS

RTS (b to a)

RTS (c to d)
Main Limitations

- The time any dialogue can last must be shorter than the time it takes for the common hopping sequence to revisit the channel being used.
- Approach is useful only if sufficiently large numbers of channels are available.
- Time sync is needed.
Approach 4: Parallel Rendezvous

- Nodes choose their own hopping sequences.
- Nodes publish the seeds of their hopping sequences so nodes can track each other.
- Key: *Parallel rendezvous* on multiple channels

Examples:
- SSCH [Bahl et al.]: senders transmit only when receivers are on the same channel.
- McMAC [So & Walrand]: senders can deviate from their published schedule temporarily to transmit.
McMAC

- Every node has its own random hopping sequence called the “home channel”.
- Hopping freq. is a parameter.
- To Tx, sender S leaves its home channel to meet its receiver R with some probability $p_{tx}$.
- If R’s channel is busy or R is away from home, S tries again later.
- Otherwise, S and R exchanges Data/Ack.
Sender needs to know the home channel of the receiver, but time sync. is not needed.
McMAC (with hopping)

<table>
<thead>
<tr>
<th></th>
<th>t=1</th>
<th>2</th>
<th>3</th>
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</tbody>
</table>

- ▲ ▲ ▲ Original schedule
McMAC (with hopping)

Original schedule

<table>
<thead>
<tr>
<th>t=1</th>
<th>2</th>
<th>3</th>
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<th>5</th>
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<td>Ch2</td>
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</tbody>
</table>

1. Data arrives
2. RTS/CTS/Data
3. Hopping stopped during data transfer
4. Hopping resumes
## Qualitative Comparison
(True? Let’s Discuss!)

<table>
<thead>
<tr>
<th></th>
<th>Control Channel</th>
<th>Split-Phase</th>
<th>Common Hopping</th>
<th>Parallel Rendez-vous</th>
</tr>
</thead>
<tbody>
<tr>
<td># Radios</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Contention Bottleneck</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Track neighbors</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
</tbody>
</table>
Simulation Parameters

- **N:** # nodes
- **M:** # channels
- **L:** avg. packet length
- **T_sw:** channel switch time
- **T_slot:** slot time = RTS/CTS
- **S:** link speed/channel (Mbps)
# Simulation Scenarios

<table>
<thead>
<tr>
<th>Scenario #1 Similar to 802.11b</th>
<th>Scenario #2 Similar to 802.11a</th>
</tr>
</thead>
<tbody>
<tr>
<td>N: # nodes</td>
<td>20</td>
</tr>
<tr>
<td>M: # chans</td>
<td>3</td>
</tr>
<tr>
<td>L: Avg Pkt Len</td>
<td>1024B / 10240B (5/50 slots)</td>
</tr>
<tr>
<td>T_sw: Switch Time</td>
<td>100us</td>
</tr>
<tr>
<td>T_slot: Slot Time</td>
<td>810us</td>
</tr>
<tr>
<td>S: Link Speed</td>
<td>2Mbps</td>
</tr>
</tbody>
</table>
20 Nodes, 3 Channels, Speed=2 Mbps

- Ctrl Chan
- Common Hop
- Split Phase
- McMAC(hop)

Goodput (Mbps)

Pkt Len (bytes)

1024
10240
Dedicated Control Channel (short pkts)
Dedicated Control Channel (long pkts)
Split Phase (12 control / 48 data slots)
Dedicated Control Channel (short pkts)
Common Hopping (short pkts)

Time (slot)

Channel
McMAC hopping (short pkts)
Conclusions by Mo, So, and Walrand

- Dedicated control channel: works surprisingly well esp. for long packets!
- Split-phase: depends heavily on the control/data phase durations
- Common-hopping: “fragmentation” problem
- Parallel rendezvous: good potential, but synchronization is an issue.
Research Opportunities

- Few schemes based on contention have not addressed collision issues.
- Efficient time sync is a requirement for multi-channel MACs, unless a dedicated control channel is used.
- Can we map prior approaches for distributed code assignment for CDMA networks to multi-channel MACs by making a code to equal a hoping sequence?
- Is topology-dependent scheduling inherently better than multiple rendezvous?
  - Impact of updating 2-hop neighborhood
- What happens when radios become really cheap and a node can receive multiple concurrent transmissions? (Same if we have MUD with MIMO)
  - What scheduling advantages do we gain?
  - What MACs can we propose?