Design and Evaluation of a new MAC Protocol for Long-Distance 802.11 Mesh Networks

by

Bhaskaran Raman & Kameswari Chebrolu

ACM Mobicom 2005

Reviewed by

Anupama Guha Thakurta

CS525M - Mobile and Ubiquitous Computing Seminar, Spring 2006
OUTLINE

• Introduction
• Background
• Protocol Design and Implementation
• Topology Construction
• Evaluation
• Discussion and Conclusions
• Comments
INTRODUCTION

• Motivations for new protocol:
  – low cost internet access to rural areas
  – achieve performance improvement over 802.11 CSMA/CA in long distance mesh networks

• 802.11 CSMA/CA MAC was designed to resolve contentions in indoor environments

• Use of wire-line, cellular or 802.16 currently prohibitive because of costs
INTRODUCTION (Cont.):

Issues Addressed

- Find an alternative to 802.11 CSMA/CA MAC protocol that allows simultaneous synchronous transmission / reception of multiple links at single node
- Propose a new MAC protocol: 2P
  - Cost advantages with off-the-shelf 802.11 hardware
  - Show dependence of 2P on network topology
  - Show that more UDP throughput than CSMA/CA is achievable (achieved 3-4 times)
  - Show that more TCP throughput than CSMA/CA is achievable (achieved 20 times)
INTRODUCTION (Cont.):
Mesh NW Characteristics

- Multiple radios per node (one radio per link)
- High-gain directional antennae
- Long distance point-to-point links of several kilometers
  - Landline node

Figure 1. 802.11 mesh: nodes have one radio per link
OUTLINE

• Introduction
• Background
• Protocol Design and Implementation
• Topology Construction
• Evaluation
• Discussion and Conclusions
• Comments
BACKGROUND

SynOp: Simultaneous Synchronous Operation (SynRx / SynTx)

- **Syn-Rx**: R1 and R2 receive simultaneously; Feasible
- **Syn-Tx**: T1 and T2 transmit simultaneously; Feasible
- **Mix-Rx-Tx**: R1 receives and T2 transmits; Not feasible

![Diagram](image)

*Figure 2. SynRx, SynTx, and Mix-Rx-Tx*
BACKGROUND (Cont.):
SynOp: Simultaneous Synchronous Operation (SynRx / SynTx)

• In 802.11 Mix-Rx-Tx is not feasible because of:
  ✓ physical proximity and side lobes of directional antennae

• In 802.11 SynOp is feasible but not allowed because:
  ✓ SynRx: IFS based immediate ACK mechanism
  ✓ SynTx: Carrier sense mechanism of interfaces give rise to backoffs
OUTLINE

• Introduction
• Background
• Protocol Design and Implementation
• Topology Construction
• Evaluation
• Discussion and Conclusions
• Comments
2P PROTOCOL DESIGN & IMPLEMENTATION

• SynOp is possible by disabling ACK and Carrier sense mechanisms
• Simple Concept: each node switches between SynRx & SynTx
• When a node is in SynRx its neighbors are in SynTx phase and vice the versa
• Bipartite Topology

Figure 4. 2P Illustration

Note: diagram ignores system and propagation delays
2P PROTOCOL DESIGN & IMPLEMENTATION (Cont.):

• Solutions for SynRx in existing hardware:

  Disable immediate ACKs’ by:
  - Independent Basic Service Set mode for interface operations, with separate SSID
  - Convert IP unicast pkts. to MAC broadcast pkts. at the driver level
  - Send ACKs’ in the LLC implemented by the driver, by piggybacking them on data packets
2P PROTOCOL DESIGN & IMPLEMENTATION (Cont.):

- Solutions for SynTx in existing hardware:
  Disable carrier-sense backoffs by:
  - utilizing the two antennae connector feature provided by Intersil Prism chipset

How it works:

- Select receiving antenna at driver level by `antsel_rx` command
- Connect external antenna to, say LEFT connector of radio card
- During transmission, the receiving antenna connector which is not connected to any external antenna is set to RIGHT
- This forces carrier-sense to happen on the RIGHT connector which sees only negligible noise
- Switch the receiving antenna to LEFT connector before switching from SynTx to SynRx

OVERHEAD?

Figure 5. Using `antsel_rx` to avoid carrier-sensing
2P PROTOCOL DESIGN & IMPLEMENTATION (Cont.): Loose Synchrony

- An interface sends B bytes in SynTx, then sends a marker packet as a "token"
- Enter the SynRx phase
- Switch to SynTx upon receiving a marker packet or upon timeout

OVERHEAD?
2P PROTOCOL DESIGN & IMPLEMENTATION (Cont.): Problems in Loose Synchrony

- Temporary loss of synchrony (marker loss)
- Link intialisation (link recovery after failure)

Solution: On entering SynRx, ifa starts a timer to control timeout
Two ends of a link get out of synchrony and timeout at the same time.

Solution: Add random perturbation (bumping) to the timeout value each time
• Coordination of interfaces to switch from SynRx to SynTx
  § Once an ifa decides to switch to Tx, it sends a notification (NOTIF) to other ifa-nbrs’, and waits for NOTIF from them.
  § Aware of UP / DOWN status of other ifa-nbrs’. (observation of 3 consecutive time-outs implies DOWN)
• Coordination of interfaces to switch from SynTx to SynRx
  § Not necessary since all ifas’ begin Tx simultaneously and with the same duration of B bytes
OUTLINE

• Introduction
• Background
• Protocol Design and Implementation
• Topology Construction
• Evaluation
• Discussion and Conclusions
• Comments
TOPOLOGY CONSTRUCTION

• Constraints in Topology

  ▪ Bipartite Constraint:
    • If a node is in SynRx its neighbors should be in SynTx and vice versa
    • Implies no odd cycles are present

  ▪ Power Constraint: For proper reception we require that
    • the signal level is above min. reqd. power level $P_{\text{min}}$
    • SINR has to be above the interference by $\text{SIR}_{\text{reqd}}$
TOPOLOGY CONSTRUCTION (Cont.):

• For a given topology
  - Power transmission $P_i$’s, $(i = 1,2,...N_A)$ are variables
  - $d(i, j)$, distance between the nodes corresponding to antennae $a_i$ and $a_j$ is known
  - $g(i, j)$, effective gain when $a_i$ is transmitting and $a_j$ is receiving, is known

Overall gain from $a_i$ to $a_j$ =
(Gain of $a_i$’s Tx in $a_j$’s dirn) ×
(Gain of $a_j$’s Rx in $a_i$’s dirn) =
Gain at angle $\alpha$ × Gain at angle $\beta$

Figure 9. Illustrating gain from $a_i$ to $a_j$
TOPOLOGY CONSTRUCTION (Cont.): Power Equations

\[
\frac{P_{2k} \times g(2k, 2k - 1)}{PL[d(2k, 2k - 1)]} \geq P_{\text{min}} \quad (1)
\]

\[
\text{Interf}(2k - 1) = \sum_{j=1, j \in I(2k)}^{N_A} \frac{P_j \times g(j, 2k - 1)}{PL[d(j, 2k - 1)]} \quad (2)
\]

\[
\frac{P_{2k} \times g(2k, 2k - 1)}{PL[d(2k, 2k - 1)]} \geq \text{SIR}_{\text{reqd}} \times \text{Interf}(2k - 1) \quad (3)
\]

Eq. 1 and 3 are power equations.
TOPOLOGY CONSTRUCTION (Cont.): Parameters in the Power Equations

- $P_{\text{min}}$: -85 dB for 11Mbps reception
- $\text{SIR}_{\text{reqd}}$: 10 dB for the $10^{-6}$ BER level, set to 14-16 dB in topology construction
- The antenna radiation pattern that decides the gain in different angles.

![Antenna Radiation Pattern Diagram](image)

Figure 10. Spatial radn. pattern: parabolic grid antenna
TOPOLOGY CONSTRUCTION (Cont.): Topology Formation

• Construct a tree topology that satisfies the two constraints
  – Suppose all (or most) traffic passes through the land-line node and don’t do multi-path routing
  – A tree rooted at the land-line node satisfies the bipartite constraint
  – Fault tolerance can be solved by morphing
TOPOLOGY CONSTRUCTION (Cont.):
Topology Formation

• Form a spanning tree with following heuristics
  – (H1) Reduce length of links used
    • Interference and power consumption
  – (H2) Avoid “short” angles between links
    • Side-lobe leakage
    • $ang_{thr}$ of 30 to 45 degrees
  – (H3) Reduce hop-count
    • Deep trees = bad latency
TOPOLOGY CONSTRUCTION (Cont.): Algorithm

1. Set of Unconnected nodes is $U$, set of all possible connection links is $S$, create links at $h_i$
2. Order the links in $S$ in increasing order of distance
3. For each link do
   - angle threshold check: ignore if angle $< \text{ang\_thr}$, else add
   - Feasibility check (power constraint equation)
4. If all nodes connected, stop.
5. If successful in adding link in step 3, continue with step 1
6. If not successful in adding link in step 3, and link formed in $h_i$, go to next link, go to step 1.
7. If not successful in adding any link, and no link formed for $h_i$, declare failure, and stop.
OUTLINE

• Introduction
• Background
• Protocol Design and Implementation
• Topology Construction
• Evaluation
• Discussion and Conclusions
• Comments
EVALUATION: of topology creation

- **Purpose**
  - The effectiveness of the algorithm
  - The effect of varying the parameter $\text{SIR}_{\text{reqd}}$

- **Evaluation subjects**
  - 4 collections of villages from a local district map
    - Q1, Q2, Q3 and Q4
    - Q1 has 31 nodes
    - Q2-Q4 have 32 nodes, respectively
  - Topologies randomly generated
    - 50 nodes in an area of 44Km X 44Km
EVALUATION: of topology creation

Figure 11. Topology formation on $Q_1$, $Q_2$, $Q_3$, and $Q_4$
EVALUATION: of topology creation

Figure 13. Topology formation on random 50-node cases
EVALUATION: of topology creation

Figure 12. An example tree created on $Q_1$
EVALUATION: simulation studies

• Goals:
  - To measure the impact that step by step link establishment has on loosely synchronized network
  - Saturation throughput performance compared to CSMA/CA protocol
  - Performance of TCP over 2P operated networks
EVALUATION: extensions to ns-2

– ns-2 extended for:
  • Multiple interface support
  • Directional antenna support
  • MAC modifications
  • LLC modifications
EVALUATION: Simulation results

- Link Establishment:
  - **Method**: add links one after another to an already synchronized network
  - **Results**:
    - Took 12.9ms for first link establishment
    - Reason: first transmission of both ends of link coincide and had to use bumping to establish link
    - Took 4.9ms for rest of the links to establish
    - No noticeable difference in throughput of already synchronized links while adding new links
EVALUATION: Simulation results

- Saturation throughput
  - UDP traffic
    - One packet every 2ms
    - Packet size: 1400 bytes
  - Results:
    - Nodes operated in 2P achieve around 3-4 times more bandwidth than operated in the CSMA/CA protocol

![Figure 14. Saturation Throughput]
EVALUATION: Simulation results

- TCP Performance
  - In loss free: Up to 20 times better performance than CSMA/CA

**Figure 15. TCP Performance: No Losses**

**Figure 16. TCP Performance: Uniform and Bursty Losses**
EVALUATION: Implementation based results

• Prototype implementation on HostAP v0.2.4 on Linux v2.4.20-8

• Confirmation of SynOp with Prism2 cards:
  ▪ 6.5Mbps throughput on each link at the same time.

• 2P performance on a single link:
  ▪ 3.05Mbps average throughput – lower than 4.4Mbps observed in simulations
  ▪ Overheads of marker pkts. And changing of antsel_rx in Prism2 cards give a combined throughput of 6.1Mbps which is less than 6.5Mbps observed.
EVALUATION: Implementation based results (Cont.)

• Sub-optimal performance of 2P on a pair of links:
  - Per interface throughput is lower than 3.05 Mbps because contention window set at 32 instead of 1 hence random backoff even in the absence of carrier sense
  - Limitations in driver level approach to 2P implementation
  - Stress of CPU scheduling involved in copying of rx/tx bytes to/from hardware as PCMCIA cards used didn’t have Direct Memory Access

<table>
<thead>
<tr>
<th></th>
<th>Avg (SD) thrpt at A (Mbps)</th>
<th>Avg (SD) thrpt at $N_1$ (Mbps)</th>
<th>Avg (SD) thrpt at $N_2$ (Mbps)</th>
<th>Avg (SD) thrpt at B (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2P</td>
<td>2.70 (0.31)</td>
<td>2.06 (0.24)</td>
<td>2.81 (0.15)</td>
<td>2.81 (0.10)</td>
</tr>
<tr>
<td>CSMA</td>
<td>2.07 (0.13)</td>
<td>1.13 (0.22)</td>
<td>1.90 (0.15)</td>
<td>3.11 (0.14)</td>
</tr>
</tbody>
</table>

Table 1. 2P on two links, versus CSMA
OUTLINE

• Introduction
• Background
• Protocol Design and Implementation
• Topology Construction
• Evaluation
• Discussion and Conclusions
• Comments
Discussion and Conclusions

• Prior work involves Spatial reuse Time Division Multiple Access (STDMA) scheduling

• The present work differs in:
  ✓ Multiple radios per node
  ✓ Directional antennae
  ✓ Exact location of nodes

• Fault tolerance and Morphing
  ➢ Trees are not very fault tolerant
  ➢ Morph the topology in the event of a failure
    - Provision additional links, but turn them on only as needed
  ➢ Morphing can be used to create new routes when network equipment is turned off
OUTLINE

• Introduction
• Background
• Protocol Design and Implementation
• Topology Construction
• Evaluation
• Discussion and Conclusions
• Comments
COMMENTS

Pros:
1. Performance enhancement
2. Low cost implementation
3. Fault tolerance solution
4. Feasible protocol

Cons:
1. Requires one dedicated transceiver for each link
2. Reconfigure on node’s joining / removal / relocation
3. Topology is centralized with multiple landlines
4. Transmit empty pkts – fairness & security