Ad Hoc and Mesh Networks: Architecture and Technology Overview

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Introduction: The Mesh Network Opportunity ....
Ad Hoc and Mesh Networks: 1st Gen Products

**Ad Hoc**

*Peer-to-peer network that allows groups of nearby users to communicate, exchange files, stream media, work collaboratively, ...*

**Mesh**

*Instantly deploy a network capable of supporting security cameras and IP data. Compare this portable and flexible solution to trenching costs or monthly circuit charges and the wireless mesh system pays for itself.*

From Firetide
Ad Hoc and Mesh Networks: Background

- Several distinct motivations for ad hoc and mesh
  - Connecting ad hoc cluster of mobile users (tactical, vehicular, P2P)
  - Networks involving embedded low-power devices (sensor nets)
  - Access without wired infrastructure (rural, developing countries)
  - Short-range radio cost-performance → wide area

- 1st generation products were for specialized markets
  - Tactical, specialized ad hoc applications
  - Sensing applications with power constraints

- 2nd gen products are for existing telecom markets, exploiting exceptional cost-performance of commodity radios...
  - Initially rural telecom, hobbyists → metro mesh today
  - Now migrating to mainstream broadband access
  - Is cellular next?
Ad Hoc and Mesh Networks: The PC Analogy

**Mainframe Computer**
~$10K/GIPS

**Cellular BTS Tower**
~$1M/Mbps (long-range)

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**Distributed PC’s**
~$0.5K/GIPS – cheap but uncoordinated CPU cycles

**Distributed PC solution dominates**
for most regimes except supercomputing

**Technical issues**: communication latency, overhead, parallel computation issues, execution control, unreliable networks, etc. → mostly solved!

**Wired High-Speed Network**
(Ethernet Switch or Internet)

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**Networked Low-Cost Radios**
~1K/Mbps – cheap short-range but uncoordinated basic transmission

**Distributed PC solution dominates**
for most regimes except supercomputing

**Technical issues**: communication latency, overhead, Concurrent transmission issues, network control, unreliable channels, etc. → not solved yet!

**Lower cost, higher capacity, more robust??**
Ad Hoc and Mesh Networks: The PC Analogy (contd.)

The $49 Mesh Node from Meraki Networks*!

1000 node metro mesh would cost just ~$50K in capital to cover a ~10 sq-Km area…!!

*Stanford and MIT student startup
Ad Hoc and Mesh Networks: Product Space

- **Mesh extends 802.11x radios to cover:**
  - Metro mesh (medium range, high capacity)
  - Access networks (extended range, lower capacity)
  - Indoor WLAN (higher capacity, coverage)

- Region of use can be even greater with new non 802.11 radios
  - Cellular wide-area equivalent
  - Switched Ethernet equivalent indoors
Ad Hoc and Mesh Networks: 2nd Gen Products

Office WLAN (faster, more scalable) than current 802.11

Metro Area Mesh Network (dense, high capacity, low cost)

Commercial vendors: Firetide, Cisco, …

Radio Nodes
~50-100 m spacing

Ad-Hoc Radio Node

Commercial vendors: Tropos, Motorola, Nortel, Nokia, …

Dual-radio ad-hoc router
(includes wired interface for AP sites)

(above photo shows WINLAB’s ORBIT node)
Ad Hoc and Mesh Networks: Problems with Current Technology

- 1\textsuperscript{st} gen, and to some extent, 2\textsuperscript{nd} gen solutions suffer from several technical problems:
  - Poor scalability – too many hops!
  - CSMA/CA MAC implies “exposed nodes” which cannot tx in parallel
  - MAC protocols never designed for multi-hop wireless to begin with!
  - Topology changes rapidly – increases routing overhead
  - Overall control overhead can be very high
  - Routing unaware of changes in PHY speed/quality
  - “Self-interference” effect for TCP flows
Ad Hoc and Mesh Networks: Technology Issues

- Products are being released, but…
  - Mobile ad hoc networks don’t really work well for tactical & vehicular
  - Mesh network performance is marginal, OK for low-cost scenarios only

- Major technical challenges are
  - Scalability (overcoming Gupta & Kumar) – hierarchies, multi-channel
  - PHY capacity improvements – collaboration, MIMO, network coding
  - Topology discovery and self-organization in mobile scenarios
  - Reducing control overheads in existing 802.11 MAC and MANET routing
  - Mitigating MAC “exposed node” problem for parallel transmissions
  - Integrated or cross-layer MAC & routing approaches without the performance problems of conventional layered protocols
  - Introducing service features such as QoS, multicast, …
  - Network Security!

- WINLAB research covers several of the above topics…
Key Technologies
Key Technologies: Hierarchical Architecture

- Hierarchical structure essential for scalability
  - Classical “Gupta & Kumar” result shows mesh throughput per node does down as \( \sqrt{n} \)
  - System can scale with multiple frequencies and proper ratio of MN, FN and AP
  - E.g, if MN~100, ~10 FN’s & ~3 AP’s needed (…note significant reduction in # wired nodes)

**Throughput per node scales ~ 1/\sqrt{n}**

“Flat” mesh network with ad-hoc routing: does not scale!

Sample experimental result on ORBIT showing linear scaling & ~2.5X capacity (for a mesh network with ~20 MN, 4FN, 2AP)
Key Technologies: Discovery and Self-Organization

- Only a subset of available links made available to routing – achieves balance between routing overhead and route availability
- Dynamic topology formation based on different such as max throughput, min delay or power

**Logical topology**

**Wired Internet Infrastructure**

**Interface One**
- Scan all channels
- Find minimum delay links to AP
- Associate with AP

**Interface Two**
- Send beacons
- Accept Associations
- Forward client Data

**Sample Result showing significant reduction in routing overhead**

**FN**
- Scan all channels, record neighbors
- Decide neighbor based on objective
- Associate with neighbor

**Interface One**

**Interface Two**

**AssocReq**

**Transmit Power Required: 1mW**

**Transmit Power Required: 10mW**

**AP**

**FN**

**Send beacons**

**Sample Result showing significant reduction in routing overhead**
Key Technologies: **Cross Layer Routing**

- Improved performance with PARMA compared to MH metric.
- PARMA has the same behavior as MTM when no congestion.

Routing Metric: \[ \sum \text{pkt size/link speed + MAC congestion} \]
Key Technologies: Multi-Channel Mesh

- Multi-channel mesh (>>1 radio per node) can improve performance significantly by supporting concurrent transmissions & reducing/eliminating 802.11 MAC overheads
  - Many 2nd gen mesh products use 5-6 radios per node
  - Algorithms for optimizing throughput given constraints on # radios, # channels
  - Possible to use 802.11a hardware and avoid MAC effects entirely
Key Technologies: Clean-Slate PHY/MAC for Mesh

- Wideband, agile short-range OFDM radio design optimized for speed
- For example, ~2 x 20 Mhz bandwidth, max bit-rate ~250 Mbps
- Additional low-bit rate PHY for control, flexible TDMA based MAC
- Radios can switch channels and bit-rates on a slot-by-slot basis (~ms) – allows for unconstrained FD/TDMA allocations

Programmable radio board at WINLAB

Note: 2 x 200 Mhz agile radios with TD capability should be sufficient for ~50 mbps duplex per node Assuming ~3-4 hops to a wired AP
**Key Technologies: Global Control Plane**

- Important architectural idea – clean separation of control & data planes
- Reduces control overhead and enables contention-free global MAC/routing algorithms
- Can use a single low rate channel (e.g. 1 mbps 802.11b) for control

![Diagram of control and data planes](http://www.uninett.no/wlan/throughput.html)
Key Technologies: Integrated Routing and MAC

- Global allocation of routes and MAC time slots at the same time to completely eliminate contention
- Allocation algorithm works on both frequency (FD) and time (TD)
- Algorithm checks for compatible time slot and freq at each receiver
- Allows for more parallel transmissions (fewer “exposed nodes”) and eliminates packet contention
- Significant performance improvement over conventional layered 802.11 + AODV etc.
- Requires GCP-type capability for distribution of control
Key Technologies: Cognitive Radio

- Cognitive radios provide PHY, MAC flexibility needed to implement cooperative multi-channel ad hoc networks with better performance
  - Cognitive radio can achieve multi-channel + flexible MAC performance
  - PHY can be optimized between neighboring nodes
  - High spectrum efficiency possible via dynamic spectrum algorithms
  - Networks may utilize a control channel similar to GCP, etc.

![Diagram of Cognitive Radio Network](image.png)
**Key Technologies:** QoS-Aware Routing

- Establishes QoS routes with reserved bandwidth on a per-flow basis
- Monitors interference from adjacent nodes
- Performs admission control to maintain network utilization below the congestion point

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**Establishes QoS routes with reserved bandwidth on a per-flow basis**

**Monitors interference from adjacent nodes**

**Performs admission control to maintain network utilization below the congestion point**

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**Key Technologies:** QoS-Aware Routing

- Establishes QoS routes with reserved bandwidth on a per-flow basis
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Key Technologies: Geocasting in Ad Hoc Vehicular Networks

- Location is a more natural addressing mechanism
  - Location becomes more important than a network address

- Opportunistic message forwarding within geographic perimeter

- Retransmissions from different vehicles

- Delay-tolerant networking

Desired message delivery zone

(Idealized) Broadcast range

Passing vehicle, in radio range for tens of seconds

Following vehicle, in radio range for minutes

Irrelevant vehicles in radio range for few seconds
Experimental Results
Experimental Results: WINLAB Prototype circa 2002

**HARDWARE**

**Access Point**
- US Robotics 2450 AP
- AMD Elan SC400 processor
- 1 MB Flash, 4 MB RAM
- Prism-2 based PCMCIA card

**Forwarding node**
- Compulab 586 CORE
- AMD Elan SC520 CPU
- 2 MB NOR flash + 64 MB NAND Flash on board
- Dual PCMCIA slots

**Sensors**
- Intrinsyc Cerfcube
- Intel PXA 250 (XScale processor)
- CF-based wireless support

**PLATFORM**

**SOFTWARE**

**Common functions:**
- Includes timer, 802.11 related
- Defines timers, state machine functionality as well as other useful wireless utilities and packet type definitions

**AP/FN/MN**
- Sensor.c, fwnode.c, ap.c
- Layer3.c
- Layer2.c
- Libnet

**Application specific functions**
- Routing
- Frame handing
- Packet handling

802.11b ad-hoc mode
Experimental Results: ORBIT Radio Grid

- ORBIT: 400 nodes in 20m x 20m—two 802.11 radios each (atheros and intel-based)
- Intended for ad hoc and mesh network studies
Experimental Results: Radio Mapping

- Suburban
- ORBIT Testbed
- Urban
- Office
- Hallway

Distances:
- 500 meters
- 300 meters
- 30 meters
- 20 meters
Experimental Results: ORBIT Proof-of-Concept for Metro Mesh Scenario

System Parameters:
0.9 sq. km,
20 mobiles/sensors,
4 FNs,
2 APs
802.11a with multiple frequencies

Flat Hierarchical System Parameters:
0.9 sq. km,
20 mobiles/sensors,
4 FNs,
2 APs
802.11a with multiple frequencies

Mapping on to ORBIT Radio grid emulator

Flat
Hierarchical

- “SOHAN” system evaluated for realistic deployment scenario with ~25 nodes

- Results show that system scales well and significantly outperforms flat ad-hoc routing (AODV)
Experimental Results: Mobility Emulation for MANET Studies

Goal: Emulate mobility for MAC and higher layers for larger number of nodes

Mapping of the actual path onto ORBIT.

Actual path.

Emulated path.
Objectives
Demonstrate a vehicular 802.11a experiment.

Actors: Sender, Receiver

Details: Receiver is stationary. Sender moves around the parking lot. Sender transmits ICMP packets addressed to the receiver. Both nodes use 802.11a, channel 36. Receiver logs per-packet RSSI using Libmac.

Results (Snapshot of RSSI)
Experimental Results: Ongoing Work

- IRMA – Integrated Routing and MAC (..requires software MAC capability under development)
  - Includes a global control plane (GCP)
  - Centralized and distributed control algorithms to be compared

- Cross-layer routing with DCMA cut-through switching MAC
  - Switched multi-radio mesh scenario
  - Based on DCMA (Acharya) MAC, distributed cross-layer routing

- Vehicular ad hoc network scenarios
  - Dense MAC experiments
  - Geocasting protocol evaluation