Cross-Layer Resource Management in Wireless Networks

Theory, Protocol Design and Implementation

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Wireless Networks

- Basic characteristics of wireless networks:
  - Wireless channels are error-prone
  - Wireless links are volatile
  - Link quality in terms of error probability and available bandwidth is time-varying
  - Wireless devices are often mobile, implying that network topology changes over time
  - The broadcast nature of wireless transmissions increases the cross-channel interference
Resource Management in Wireless Networks

• **General Problem**: Wireless networks are signified by scarce bandwidth resources that need to be allocated carefully in order to achieve adequate user performance and efficient utilization of the wireless channel

• **Current situation**:
  • The currently employed wireless network protocols and control mechanisms extract only a small fraction of available network transport capacity
  • The provisioned quality of service is primarily best-effort without any guarantees or any notion of optimal performance

• Need for new solutions that will achieve improved network throughput, considerably reduced end-to-end delay and facilitate close-to-optimal network operation
Resource Management: Our Methodology

View the network as a continually evolving dynamic system that needs to be appropriately controlled and optimized.

- Theoretical study
- Algorithm/Protocol design
- Implementation
How to manage the available resources in IEEE 802.11 wireless networks?
How to manage the available resources in IEEE 802.11 wireless networks?
Cross-Layer Association in 802.11-based Wireless Networks
User Association in 802.11 Wireless Networks

- Scanning phase
  - Passive scanning
  - Active scanning
- Decision phase
- Association phase

**Association decision** → Received Signal Strength (RSSRI) of the Beacons or Probe Requests sent by APs
User Association in 802.11 Wireless Networks

- **Main problem in this mechanism:**
  - RSSRI is not an appropriate decision factor for user association (high RSSRI values cannot univocally indicate high throughput)
    - RSSRI not only depends on the distance from the APs, but also on the transmission powers of the APs
    - RSSRI is an indicator for the downlink but not for the uplink channel conditions
    - Throughput depends on the population of the cell served by the APs
Throughput in 802.11 Wireless Networks

• When there are several flows with different physical transmission rates, then the throughput of all flows is bounded by the slowest transmission rate [1][2].

• We consider the simple case, when all nodes \((n)\) have the same back-off parameters, each node is the transmitter for a single flow, and all packets have lengths are equal to \(L\). The total average network throughput is [3]:

\[
\theta(\beta) = \frac{n\beta(1 - \beta)^{n-1}L}{1 + \sum_{i=1}^{n} \beta(1 - \beta)^{n-1}(\frac{L}{C_i} + T_0) + (1 - (1 - \beta)^n - n\beta(1 - \beta)^{n-1})T_c}
\]

Where \(\beta\) is the attempt rate (probability), \(C_i\) is the physical transmission rate of node \(i\), \(T_0\) is the fixed overhead with packet transmission and \(T_c\) is the fixed overhead for an RTS collision.

Packet Delay in 802.11 Wireless Networks

- Average per packet delay is:

\[ \rho(n) = \frac{L}{\theta(\beta)} = \frac{1}{n\beta(1-\beta)^{n-1}} + (T_0 - T_c) \left\{ \frac{1 - (1 - \beta)^n}{n\beta(1-\beta)^{n-1}} T_c + \frac{1}{n} \sum_{i=1}^{n} \frac{L}{C_i} \right\} \]

- For each packet attempted to be transmitted, it would be in error due to channel errors with probability \( e_{pt} \)

- Average number of attempts until successful transmission: \( 1/(1 - e_{pt}) \)

- For each attempt, on the average, \( \rho(n) \) amount of time is experienced.

- The production of \( 1/(1 - e_{pt}) \) and \( \rho(n) \) gives the average delay of a successful transmission.

Performance metric

Objective \( \min \) (Airtime cost)
Airtime Metric for STA Association

- **Airtime metric** → represents the average duration for which the channel is occupied by a transmission.
- **Airtime cost of station** $i \in U_\alpha$ where $U_\alpha$ is the set of stations associated with AP $a$:

$$C^i_\alpha = \left[ O_{ca} + O_p + \frac{B_t}{r_i} \right] \frac{1}{1 - e^{i}_{pt}}$$

$O_{ca}$ is the channel access overhead, $O_p$ is the protocol overhead and $B_t$ is the number of bits in the test frame. The input parameters $r_i$ and $e^{i}_{pt}$ are the bit rate in Mbs, and the frame error rate for the test frame size $B_t$.

Airtime Metric for STA Association

• Load on the “uplink” channel of a particular AP $a$:

$$C_{a}^{up} = \left[ O_{ca} + O_{p} + B_{t}(1/r_{up}) \right] \frac{1}{1 - e_{pt}} |U_{a}|$$

where $\bar{e}_{pt}$, $r_{up}$ and $|U_{a}|$ are the average uplink error probability, average uplink transmission rate and the number of STA associated with AP $a$

• Load on the “downlink” channel of a particular AP $a$:

$$C_{a}^{down} = \left[ O_{ca} + O_{p} \right] \sum_{j \in U_{a}} \frac{1}{1 - e_{pt}^{j}} + B_{t} \sum_{j \in U_{a}} \frac{1}{r_{j}(1 - e_{pt}^{j})}$$
Execution of the Airtime Mechanism

Load on the “uplink” channel + Load on the “downlink” channel

Total association cost

Association decision
Cross-Layer Association Mechanism

- We extend the previous scheme by considering the end-to-end QoS that each user faces
- End-to-end QoS → incorporated in the association process of a station with a MAP
- RM-AODV (Radio Metric Ad-Hoc On Demand Distance Vector) introduces the airtime link cost as a routing decision metric
RM-AODV

1. Source (S) initiates RREQ (m=0).
2. Node C forwards RREQ (m=13, prev=A).
3. Node B receives RREP (m=13) and forwards it.
4. Node D forwards RREP (m=3) to the destination (A).
5. Node A forwards RREQ (m=10) with a better metric.
6. Node B forwards RREP (m=10) with a better metric.
7. Node C forwards RREQ. However, the destination does not reply because the metric is no better.
Cross-Layer Association Mechanism

- The association airtime cost and the routing airtime cost are weighted by the station that initiated the association scanning:

\[
TC_{i}^{rcv} = (AC_{i}^{up} + AC_{i}^{down})w_1 + RC_{i}^{rcv}w_2
\]

where \( TC_{i}^{rcv} \) is the total weighted cost calculated for MAP \( i \), \( AC_{i}^{down} \), \( AC_{i}^{up} \) are the association airtime costs for the uplink and downlink respectively (we used symbol C before), \( RC_{i}^{rcv} \) is the routing airtime cost for the path from MAP \( i \) to the receiver \( rcv \) and \( w_1, w_2 \) are the weights.
Execution of the Cross-Layer Mechanism

Load on the “uplink” channel +
Load on the “downlink” channel +
Routing airtime cost

Total cost

Association decision
Evaluation

- Extensive OPNET simulations
- RM-AODV is implemented
- Clients are uniformly distributed (at random)
- All nodes use a default transmit power of 20 dBm
- Apply different topologies in order to get accurate results
- Compare to 3 association schemes
Simulation Results

44% throughput improvement

Channel Quality based: B. Kauffmann, F. Baccelli, A. Chaintreau, V. Mhatre, K. Papagiannaki and C. Diot
"Measurement-Based Self Organization of Interfering 802.11 Wireless Access Networks" In IEEE Infocom, Anchorage, Alaska, May, 2007

Simulation Results

![Graph showing simulation results for different metrics: Airtime Metric based, Channel Quality based, Network Directed, and 802.11. The x-axis represents the number of stations, ranging from 5 to 55, and the y-axis represents average delay in seconds, ranging from 0 to 0.12. The graph illustrates the performance comparison among the different metrics as the number of stations increases.]
Simulation Results

![Graph showing simulation results for different metrics such as Airtime Metric based, Channel Quality based, Network Directed, and 802.11. The graph plots dropped data (bits/sec) against the number of stations. Each metric is represented by different markers and lines, showing how the dropped data increases with the number of stations.]
Routing-Aware Channel Selection in Multi-Radio Mesh Networks
Interference in 802.11 Wireless Networks

IEEE 802.11 standard → Channels are arbitrarily selected by the users
802.11 Wireless Networks

Demand for high throughput wireless internet connectivity

Solution

Thousands of WLANs are deployed in urban areas

Problem

Increased amounts of interference and contention among co-channel access points (limited number of available communication channels, 3 for 802.11g and 11 for 802.11a). The end users get low throughput in the long term.
Mesh Environments

- Efficient channel selection in 802.11 mesh deployments

Minimize contention and interference among co-channel devices and thereby supporting a plurality of QoS-sensitive applications.
Mesh Environments

- Information has to be routed via multiple wireless hops before it can reach the destination.
- Intermediate mesh hops along a route need to operate in frequencies, where contention and interference are as low as possible.

How can we allocate frequencies in a mesh network, in order to maximize the total network throughput, in a distributed manner?
Mesh Environments

- Frequency selection algorithms should prioritize the assignment of low-interference channels at highly-loaded mesh links, both at the access and the backhaul levels.

- Both the *frequency selection* and *load-aware routing* functionalities are inter-dependent and must be considered in conjunction.
Motivating Our Channel Allocation Policy Through 802.11 Testbed Measurements

Active routes:
- a) 16→15→20→19
- b) 13→15→20→14

Channel allocation policies:
- A1: Allocates the channel with the minimum aggregate interference, observed through RSSI measurements
- A2: Takes into account the link loads, in terms of both link quality and aggregate traffic service
ARACHNE*: A Routing-Aware CHANNEL Selection Protocol in Multi-Radio Mesh NETworks

• Load and routing aware channel selection protocol for wireless mesh networks

• Performs end-to-end channel selection along a route, by adopting a variation of a load characterization metric (airtime metric)

• Combines frequency selection and route selection under the same unified framework

*In Greco-Roman mythology, Arachne was a great mortal weaver who boasted that her skill was greater than that of Minerva (She was the Etruscan counterpart to Greek Athena). The offended goddess set a contest between the two weavers. Minerva destroyed Arachne's tapestry and loom. Ultimately, the goddess turned Arachne into a spider. Arachne simply means "spider" (αράχνη) in Greek.
Airtime Metric for Channel Selection

- **Airtime metric** → Reflects the load on a wireless router in terms of the average delay a transmission of a unit size packet experiences (approximates the per packet latency)

- Airtime cost of station $i$ associated with AP $a$, that communicate using channel $c$:

\[
C_{a,c}^i = \left[ O_{ca} + O_p + \frac{B_t}{R_{i,c}^a} \right] \frac{1}{1 - e_{pt}^c}
\]

- $O_{ca}$: channel access overhead, $O_p$: protocol overhead, $B_t$: number of bits in the test frame, $R$ and $e_{pt}$ are the bit rate in Mbs, and the frame error rate for the test frame size $B_t$

2. George Athanasiou, Ioannis Broustis, Thanasis Korakis and Leandros Tassiulas, "Routing-Aware Channel Selection in Multi-Radio Mesh Networks", in IEEE ICC 2009, Dresden, Germany, June 2009
Airtime Metric for Channel Selection

- Average airtime cost (in one direction: uplink or downlink) of AP $a$ with $N_a$ users that operates on channel $C$:

$$
\overline{C}_{a,c} = \frac{1}{N_a} \sum_{i=1}^{N_a} \left[ O_{ca} + O_p + \frac{B_t}{R_{i,a,c}^c} \right] \times \frac{1}{1-e_{pt}^c}
$$

- The average airtime cost on in the uplink and the downlink reflects the channel performance (in both directions, approximates the per packet latency) and therefore approximates the maximum throughput in a cell.

- Minimum airtime cost **approximately** Maximum throughput
Why Airtime Metric is Efficient for Channel Selection?

In presence of interfering cells in the network

- Number of erroneously received packets increases
- Transmission rate decreases

Captured by the airtime metric (function of error rate and transmission rate)

Assign channels to mesh nodes, such that the average airtime metric is minimized, both at the access and the backhaul levels.
Channel Selection at the Access Level

- Communication of the end hosts (clients) with mesh nodes at the edge of the backhaul

- **[1]**: AP computes the average downlink airtime cost
  - At the nominal start of ARCHNE, AP sets a special bit in its beacon template, thereby informing its STAs that the airtime calculation process has been initiated

- **[2]**: AP computes the average uplink airtime cost
  - The STA can include their airtime cost in their measurement report massages (802.11k) or they can piggy-back this information through their data frame transmissions towards AP
Channel Selection at the Access Level

- **[3]**: Decide if the current channel is appropriate using a threshold

- **[4]**: Computing the average airtime cost of the rest available channels if necessary

Diagram:
- Average uplink and downlink airtime cost for channel $c > T$
  - **YES**: Remain at the same channel
  - **NO**: Initiate a channel discovery process and measure the performance of the next channel (switch to the next channel and repeat steps 1-3)
  - **NO**: Visit all available channels and select the channel with the minimum average airtime cost
Channel Selection at the Mesh Backhaul

- Serve the forwarding of packets to their final destinations
- RM-AODV is applied at the mesh backhaul and several routes go through the mesh APs

Wireless interfaces

- **IN**: Used for data reception
- **OUT**: Used for data forwarding

Each node can assign channels only to its **OUT** interfaces. The **IN** interfaces follow the channels that are assigned by the nodes that communicate with the current node.
Channel Selection at the Mesh Backhaul

• [1]: Constructing a priority list
  • APs broadcast their load (priority rank)
  • Each AP knows the priority of all mesh APs in the network
  • Rule: The higher the load (data that must be forwarded), the higher the priority in selecting channel

• [2]: Assigning route sessions to available OUT interfaces
  • Load is balanced to the available OUT interfaces at each mesh APs
Channel Selection at the Mesh Backhaul

• [3]: Assigning channels to OUT interfaces
  • Coordination with the IN interface of the mesh AP that receives the traffic is required
  • Respect the priority list
  • Select the channel with the minimum airtime cost
  • Send an RTC frame announcing the new channel
  • IN interface responds with a CTC and starts using the new channel
  • IN interface responds with an XTC in case that there are no available IN interfaces to assign the new channel

• [4]: Selecting channels in an iterative way
  • Repeat the previous procedure till convergence
Evaluation

- Extensive OPNET simulations, which import both synthetic and real traces
- RM-AODV is implemented
- Clients are uniformly distributed (at random)
- All nodes use a default transmit power of 20 dBm
- Apply different topologies in order to get accurate results
- Types of traffic: a) Saturated UDP, b) VoIP, c) Real traces (Dartmouth college, IBM)
- Compare the network performance with ARACHNE, against the single-channel assignment, a random-channel allocation strategy, as well as the Hyacinth protocol proposed in literature
UDP and VoIP

**UDP**

**VoIP**

Real Traces (Dartmouth College & IBM)

(a) Dartmouth traces (2 interfaces).

(b) IBM traces (2 interfaces).

(c) Dartmouth traces (4 interfaces).

(d) IBM traces (4 interfaces).
Experimental Evaluation of Resource Management Mechanisms in 802.11 Wireless Networks
Experimental Evaluation

- MADWIFI (Multiband Atheros Driver for Wireless Fidelity) driver
- Open source Linux kernel device driver for Wireless LAN chipsets
- Build on-top of the current implementation of 802.11
- Several indoor and outdoor wireless nodes (2 wireless interfaces)
UTH/NITOS Wireless Testbed*

- Linux server
  - The server provides
    - NFS support for mounting the OS
    - Access to the OMF ORBIT management system
  - 15 ORBIT nodes deployed ([http://www.orbit-lab.org](http://www.orbit-lab.org))
    - They mount a Debian Linux over NFS, kernel v2.6
    - 2 Wireless cards, Atheros, chipset: AR5212, MadWifi driver
    - 1 GHz VIA C3 CPU, 512 MB RAM, 40 GB HDD, 2 IEEE 802.11 a/b/g cards
  - Several end user devices
  - Switch: 10/100 D-Link Ethernet switch, 24 ports, PoE.

*Part of OneLab2 and OpenLab EU Projects
MADWIFI - Open Source Driver Support

- Linux based
- Open source drivers: modification of the MAC layer
- Implementation of MAC/Network cross layer algorithms
- 802.11 network cards: implementation is backward compatible with current WiFi products
- The performance of the implemented protocols can be directly compared with the commercial 802.11 solutions
Mechanism Implementation

• MADWIFI v0.9.4

• We have changed the RSSI-based association functionality that is implemented in MADWIFI and we have introduced our airtime-based association mechanism.

• We have extended the management frames (beacon frames) in order to carry useful information about the operational parameters of the APs in the network

• We have implemented RM-AODV on top of the current implementation of AODV

• We have implemented ARACHNE
Implementation Details – Airtime Measurement

• Every AP must measure and broadcast periodically the cumulative airtime cost in both directions (uplink and downlink):

  • Each AP measures the transmission rate and the packet error rate (based on the transmission of the data frames) at each downlink communication and then computes the cumulative airtime cost for its downlink. As far as the computation of the packet error rate is concerned, we capture the percentage of the dropped data frames in a time window.

  • Each associated STA captures the percentage of the dropped data frames in order to compute the packet error rate in its uplink. Then, the STAs compute their uplink airtime cost and piggy-back its value in their data frames. This is a practical way to inform the AP about the quality of the uplink communications.

  • Each AP computes the cumulative airtime cost in both directions based on the previous measurements.

  • Each AP periodically broadcasts the cumulative airtime cost (in its beacon frames). In order to incorporate the aforementioned value in the beacon frame we have overwritten some of its fields.
Implementation Details – Mechanism Execution

• Each STA that tries to find an AP to be associated with, initiates a scanning procedure.

• During the scanning procedure STA receives the transmitted beacon frames and captures the cumulative airtime cost of the candidate APs for association.

• Then, the STA decides to be associated with the AP with the minimum airtime cost.
Experimental Results

1st scenario: 5 APs (there is no co-channel interference)

52% improvement

56% improvement
Experimental Results

2\textsuperscript{nd} scenario: 5 APs (there is co-channel interference)

84% improvement

62% improvement
Conclusions

• Universal **airtime metric** for end-to-end cross-layer resource management in 802.11-based wireless networks:
  
  • **Association Control**
  
  • **Resource-Aware Routing**
  
  • **Load-Aware Channel Selection** *(At the access part)*
  
  • **Routing-Aware Channel Selection** *(At the mesh backhaul)*
  
• Simulation-based evaluation *(OPNET)*

• Implementation and experimental evaluation in a small scale wireless testbed *(MADWIFI, ORBIT hardware)*

• The proposed mechanisms introduce significant performance improvement compared to 802.11 and to several approaches in literature
Thank you!

More information @ www.athan.eu