Network Utility Maximization for overcoming inefficiency in multirate wireless networks

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Wireless networks are increasingly prevalent for Internet Access.
The IEEE 802.11 protocol is the most used wireless access mechanism.
We want to understand the resource sharing this protocol produces in the network.
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Some questions we want to answer:

- Which is the throughput obtained by TCP connections in a 802.11 environment?
- Which is the resource allocation when multiple transmission rates are present?
- Can we do better?
Our contributions

- We characterize the impact of overheads in TCP over 802.11 for the different available rates.
- We characterize the resource sharing in a single cell with multiple TCP connections.
- We identify the inefficiencies of the current allocation.
- We propose a new allocation based on Network Utility Maximization (NUM).
- We present an AQM policy that enables the new allocation.
- We discuss how to generalize these algorithms to more complex scenarios.
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1. Impact of overheads in TCP over 802.11.

2. TCP resource allocation in a multirate wireless environment

3. A more efficient resource allocation for a single cell

4. Extension to general network topology

5. Implementation and simulations

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Things that affect performance

- 802.11 Protocol overheads.
- CSMA/CA access algorithm.
- Number of users in the cell.
- Position of users in the cell (through modulation rate).
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- 802.11 Protocol overheads.
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IEEE 802.11 basics

- IEEE 802.11 uses DCF as the main access mechanism to the shared medium.

- Moreover, transmitting a packet of size $L$ bits involves some amount of overhead due to MAC and PHY headers (e.g. PLCP).

- Therefore, the real transmission rate of packets is not “54Mbps” but less. How much?
Consider the case of downlink transmissions, where the station that predominantly accesses the medium is the AP.

The AP will perform the DCF algorithm even if the chance of collision is low since STAs are not trying to access the medium (except possibly for TCP ACKs).

The total time to send a packet to station $STA_i$ with PHY rate $PHY_i$ is:

$$T_i^0 + K\sigma = DIFS + K\sigma + H + \frac{L}{PHY_i} + SIFS + MAC\_ACK_i$$

where $K \sim U\{0, \ldots, CW\}$ is the (random) number of backoff slots.
### Typical 802.11 parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot time $\sigma$</td>
<td>9 $\mu$s</td>
</tr>
<tr>
<td>$SIFS$</td>
<td>10 $\mu$s</td>
</tr>
<tr>
<td>$DIFS$</td>
<td>28 $\mu$s</td>
</tr>
<tr>
<td>PLCP Header $H$</td>
<td>24 $\mu$s</td>
</tr>
<tr>
<td>$PHY_i$</td>
<td>6Mbps ... 54Mbps</td>
</tr>
<tr>
<td>$CW_{min}$</td>
<td>15 slots</td>
</tr>
<tr>
<td>$MAC_ACK$</td>
<td>24 $\mu$s</td>
</tr>
</tbody>
</table>

**Table:** Typical IEEE 802.11g parameters
By a renewal reward argument, in the long range the MAC rate will be:

\[ C^0_i = \frac{L}{E[K\sigma + T^0_i]} = \frac{L}{\frac{CW_{min}}{2}\sigma + T^0_i} \]

We shall denote \( T_i = \frac{CW_{min}}{2}\sigma + T^0_i \) the average time to send a packet to station \( i \).

Note that the MAC rate depends on the packet size. In the future we will fix \( L = 1500 \) bytes.
Beware of TCP ACKs!

- The previous model does not take into account the TCP ACKs that go in the uplink direction.
- TCP ACKs were designed to have low impact on the reverse path (40 bytes against 1500).
- However, due to the 802.11 overheads, their impact is greater: The effective rate becomes:

\[
C_i = \frac{L}{T_i + TCP\_ACK_i}
\]

\(TCP\_ACK_i\) is the average time to transmit a \(TCP\_ACK\) packet:

\[
TCP\_ACK_i := DIFS + H + \frac{CW_{min}}{2} + \frac{L_{ack}}{PHY_i} + SIFS + MAC\_ACK_i,
\]

and \(L_{ack}\) is typically 40 bytes.
### The real 802.11g data rates with TCP

<table>
<thead>
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<th>MAC rates ($C_i^0$)</th>
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<tr>
<td>54</td>
<td>31.9</td>
<td>22.4</td>
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<td>48</td>
<td>29.7</td>
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</tr>
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</tr>
<tr>
<td>18</td>
<td>14.6</td>
<td>12.1</td>
</tr>
<tr>
<td>12</td>
<td>10.4</td>
<td>8.9</td>
</tr>
<tr>
<td>6</td>
<td>5.57</td>
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**Table:** MAC rates for the corresponding PHY rates of 802.11g in Mbps. $L = 1500$ bytes.
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Table: MAC rates for the corresponding PHY rates of 802.11g in Mbps. $L = 1500$ bytes.

The TCP ACKs waste 25% of the bandwidth at high rates!
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The issue of multiple rates

- From now on we consider only the effective rates $C_i$ as given.
- We will focus on the resource allocation provided by TCP in the presence of these multiple rates.
- Why are multiple rates an issue? An example...
The issue of multiple rates

**Point of Presence**

- **Internet Access**
- **802.11 AP**

**Coverage Area**

- **Class 1**
- **Class 2**
- **Class 3**
The issue of multiple rates

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NUM in multirate wireless networks

802.11 AP

Class 1
Class 2
Class 3

Coverage Area
The issue of multiple rates

- **Internet Access**
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  - Class 1
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NUM in multirate wireless networks
The issue of multiple rates
Assume:

- $N$ stations are downloading data from a single Access Point (AP).
- Each station $i$ has a wireless data rate $C_i$.
- Data is queued at the AP. The input rate for connection $i$ is $x_i$ and the output rate $y_i$.

Packets are served FIFO. The Head of Line probability is modeled as:

$$p_{HOL,i} = \frac{x_i}{\sum_j x_j}$$

And thus we have:

$$y_i = \frac{p_{HOL,i}L}{\sum_j p_{HOL,j}L/C_j} = \frac{x_i}{\sum_j x_j/C_j}$$
TCP can be modelled as adapting rate according to some congestion signal.

\[ \dot{x}_i = k(x_i)(U'_i(x_i) - p_i) \]

where \( U(x) \) is an increasing and concave utility function, \( p_i \) is the congestion signal and \( k(x_i) > 0 \) a scale factor.

For TCP/Reno like algorithms we can take \( p_i \) the loss probability.

The utility function represents the *protocol desire* for bandwidth and is typically chosen as \( U'(x) = Kx^{-\alpha} \) with \( \alpha > 0 \) a parameter which determines the compromise between efficiency and fairness of the allocation.

Example: TCP/Reno takes \( \alpha = 2 \).
To complete the loop, we model the loss probability as the proportion of excess rate.

The loss probability for station $i$ becomes:

$$p_i = \left( \frac{x_i - y_i}{x_i} \right)^+ = \left( 1 - \frac{1}{\sum_j x_j / C_j} \right)^+ = p$$

which is simply the proportion of packets that exceed the current service rate ($\cdot^+ = \max(\cdot, 0)$).
Putting the previous equations together we have the following model:

\[
\dot{x}_i = k(x_i)(U'_i(x_i) - p),
\]

\[
p = \left(1 - \frac{1}{\sum_j x_j/C_j}\right)^+.
\]

which is a Kelly [3, 7] type model of TCP behavior, adapted to the multiple rates scenario of wireless networks.

TCP over 802.11: the downlink model
Putting the previous equations together we have the following model:

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which is a Kelly [3, 7] type model of TCP behavior, adapted to the multiple rates scenario of wireless networks.

Which is the equilibrium of these dynamics?

Is this equilibrium globally asymptotically stable?
Consider the function:

$$\Phi(x) = \sum_{i} \frac{x_i}{C_i} - 1 - \log \left( \sum_{i} \frac{x_i}{C_i} \right),$$

whenever $\sum_{i} \frac{x_i}{C_i} > 1$ and 0 otherwise.

We have the following:

**Lemma**

$\Phi$ is a convex function of $x$. 
Consider now the following convex optimization problem:

Problem 1

\[
\max_x \sum_i \frac{1}{C_i} U_i(x_i) - \Phi(x)
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\]

We have the following:

Theorem

*The equilibrium of the TCP dynamics is the unique optimum of Problem 1.*
The main result of this section is:

**Theorem**

*The equilibrium of the TCP dynamics is globally asymptotically stable.*

**Proof sketch.**

Take $V(x) = \sum_i \frac{1}{C_i} U_i(x_i) - \Phi(x)$ as a Lyapunov function for the system (details in the paper).
Problem 1 can be interpreted as a barrier function approximation of:

**Modified Network Problem**

\[
\max_x \sum_i \frac{1}{C_i} U_i(x_i)
\]

subject to the constraint:

\[
\sum_i \frac{x_i}{C_i} \leq 1
\]
The modified Network problem

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this problem generalizes the Network problem of [3] to the wireless scenario, with two variants:

- The constraint is rewritten in terms of \(x_i/C_i\), the “time proportion” the shared medium is used by connection \(i\).
- The scaling factor \(C_i\). This implies a negative bias to users with higher rates, since they would have less weight in the net utility.

Which is the effect of this bias?
Remark

In the case where all users share a common utility function (e.g. equal RTT TCP/Reno connections), the solution of the MNP reduces to

\[ x_i^* = \frac{1}{\sum_j 1/C_j}, \]

which is the harmonic mean of the data rates.

- This is in accordance with [4] where this rate is obtained as an upper bound on the realistic rate permanent connections experiment, and collisions are considered.
- As compared with [4], in our result the behavior of TCP is fully taken into account.
Consider the following example:

- 3 users are downloading data from a single AP.
- Common utilities $U(x) = -\frac{1}{\tau^2 x}$ which model the TCP/Reno response.
- MAC layer rates are $C_i = 10$

In this case: $x_i^* = 3.333$ for all three users.
Consider the following example:

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In this case: \( x_i^* = 3.333 \) for all three users.

If user 3 for instance changes its radio conditions to \( C_3 = 1 \), the new allocation results:

\[
x_1^* = x_2^* = x_3^* = 0.8333.
\]

Note that the fastest destinations are heavily penalized due to the user 3 inefficiency.
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Issues with the current allocation

- The current implementation of TCP over wireless induces inefficiency.
- The MAC layer actually determines the allocation (as in previous example).
- This allocation is fair (in max-min sense).
- Can we sacrifice this in order to get more throughput?
The natural problem to solve would be:

**Wireless Network Problem**

$$\max_x \sum_i U_i(x_i)$$

subject to the constraint:

$$\sum_i \frac{x_i}{C_i} \leq 1,$$

The purpose of this section is to analyze how to achieve the this optimum without resorting to a complicated scheduling mechanism in the AP.
Properties of the new allocation

To see the difference, consider the following interesting property:

**Proposition**

If \( U(x) = K \log(x) \) for all connections, then the equilibrium of WNP is \( x_i^* = C_i/n \). In particular, the allocated rate for user \( i \) depends only on its own effective rate and the total number of users.

- This shows that imposing proportional fairness protects the fastest users from the lower rate ones.
- If \( U(x) \) is chosen for TCP/Reno we have an intermediate situation.
Achieving the WNP optimum

Consider the Lagrangian of WNP:

\[
\mathcal{L}(x, p) = \sum_i U_i(x_i) - p \left( \sum_i \frac{x_i}{C_i} - 1 \right).
\]

A simple primal-dual gradient algorithm to solve this optimization problem is:

\[
\dot{x}_i = k(x_i) \left( U'_i(x_i) - \frac{p}{C_i} \right),
\]

\[
\dot{p} = \left( \sum_i \frac{x_i}{C_i} - 1 \right)_{p}^+. 
\]

It is well known [1, 2] that the trajectories of these dynamics converge globally to the optimum of WNP.

Questions: what is \( p \)?, how to implement this?
In congestion control literature, the dual variable has been interpreted as queueing delay [5, 6].

This is also the case here! Let $b_i$ denote the amount of data of connection $i$ in the buffer, then:

$$\dot{b}_i = x_i - y_i$$

and the delay $d$ is given by:

$$d = \sum_i \frac{b_i}{C_i}.$$  

Therefore, recalling the definition of $y_i$ we have:

$$\dot{d} = \sum_i \frac{\dot{b}_i}{C_i} = \sum_i \frac{x_i}{C_i} - 1.$$  

Observe further that when all capacities are equal $C_i = C$ we recover the delay based model of [5, 6].
However, connections must react to a price *scaled* by $C_i$.

$$
\dot{x}_i = k(x_i) \left( U'_i(x_i) - \frac{p}{C_i} \right)
$$

Moreover, typical TCPs react to *losses* instead of *delay*.

Can we overcome this issue?
But this price must be scaled...

- However, connections must react to a price scaled by $C_i$.

$$\dot{x}_i = k(x_i) \left( U'_i(x_i) - \frac{p}{C_i} \right)$$

- Moreover, typical TCPs react to *losses* instead of *delay*.
- Can we overcome this issue?
- **Answer:** apply a Multirate RED algorithm in the queue.
The Multirate RED algorithm (MRED)

- **MRED**: is a simple Active Queue Management policy.
- **Idea**: use buffer content $b$ as a proxy for queueing delay.
- The AP discards packets randomly with probability $p_i$ proportional to $\frac{b}{C_i}$ for connection $i$.

Remark: we discard more packets when the buffer is full, and when the data rate is low.

Moreover, this mechanism can be implemented in the AP resorting only to local information (dst. address, current rate).
The closed loop dynamics of MRED

The closed loop dynamics for the proposed system is:

\[
\dot{x}_i = k(x_i) \left( U_i'(x_i) - \frac{\kappa b}{C_i} \right),
\]

\[
\dot{b} = \left( \sum_i x_i - y_i \right)_{b}^+ = \left( \sum_i y_i \right) \left( \sum_i \frac{x_i}{C_i} - 1 \right)_{b}^+.
\]

where \( \kappa > 0 \) is the proportionality constant of RED.

These equations are similar to a primal-dual algorithm.

In equilibrium, the \( x_i \) and \( p = \kappa b \) will satisfy the KKT conditions of WNP.

Stability results for these equations are harder to obtain, we explore its behavior by simulation.
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We would like to extend the previous analysis to general topologies, in particular:
- mixed wired-wireless networks.
- multi-hop wireless.

Which constraints we have? 3 classes:
- Classical wired: \( \sum_i x_i \leq c \).
- Wireless multirate: \( \sum_i \frac{x_i}{c_i} \leq 1 \).
- Contention between cells constraints: \( \sum_j \alpha_j \leq 1 \), where \( \alpha_j \) is the proportion of time each contending node is using the shared medium.
Some notation...

- Network with \( J \) nodes \((j)\) and \( L \) links \((l)\).
- Links can be wired or wireless, with effective capacity \( c_l \).
  \[ C = \text{diag}(c_l). \]
- \( i = 1, \ldots, n \) represent the connections, with rate \( x_i \).
- \( R \) is the classical routing matrix:
  \[ R_{li} = 1 \text{ if connection } i \text{ traverses link } l. \]
- We group the links in *contention sets* that cannot be used simultaneously.
- \( G \) is the *contention matrix*:
  \[ G_{kl} = 1 \text{ if link } l \text{ belongs to contention set } k. \]
We propose to optimize:

\[
\max_x \sum_i U_i(x_i)
\]

subject to:

\[
Hx \leq 1.
\]

where:

\[
H = GC^{-1}R
\]

and 1 is a column vector of ones.
Example: wireless distribution scenario

Consider the following topology:

**Figure:** Mixed wired-wireless distribution system with 4 end-users.
Example: wireless distribution scenario

We can model the capacity constraints of this network with the above framework by taking:

\[
G = \begin{pmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 \\
\end{pmatrix}
\]

\[
R = \begin{pmatrix}
1 & 1 & 1 & 1 \\
1 & 1 & 0 & 0 \\
0 & 0 & 1 & 1 \\
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{pmatrix}
\]

and

\[
C = diag(c, c_{AP1}, c_{AP2}, c_1, c_2, c_3, c_4)
\]
Example: wireless distribution scenario

- Using the previous matrices the constraints become:

\[
\frac{x_1}{c} + \frac{x_2}{c} + \frac{x_3}{c} + \frac{x_4}{c} \leq 1
\]

\[
\frac{x_1}{c_{AP_1}} + \frac{x_2}{c_{AP_1}} + \frac{x_3}{c_{AP_2}} + \frac{x_4}{c_{AP_2}} \leq 1
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\[
\frac{x_1}{c_1} + \frac{x_2}{c_2} \leq 1
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which generalize the previous “time proportion” constraints in the single-cell model.
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which generalize the previous “time proportion” constraints in the single-cell model.

Questions: which is the correct price? can we decentralize the solution?
By taking the Lagrangian of the general NUM problem and applying a primal-dual algorithm, we find that the correct price is again queueing delay at each contention graph.

But it also must be scaled by link capacity.

If there is a queue associated, then the price can be generated via MRED.

However, decentralization is not always possible (details in the paper).

Decentralization is indeed possible in tree topologies (like the previous example).
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Implementing MRED in ns-2

- We implemented the proposed algorithms in ns-2
- Two main issues were solved:
  - We adapted the dei80211mr library to implement destination based PHY rate to reflect the real behavior of APs.
  - We programmed the MRED algorithm in a new Queue object that talks to the MAC layer.
We implemented the proposed algorithms in ns-2

Two main issues were solved:

- We adapted the dei80211mr library to implement destination based PHY rate to reflect the real behavior of APs.
- We programmed the MRED algorithm in a new Queue object that talks to the MAC layer.

The algorithm: whenever a packet for next-hop $j$ is received, it is discarded with probability $p_j = \kappa b / C_j$

- $\kappa$ acts as a scaling parameter.
- $b$ is the current queue length.
- $C_j$ is the corresponding effective rate for the current modulation rate the AP maintains with destination $i$.
- For wired links, $C_j = C$, the link capacity.
Scenario 1: Single-cell

We simulated the following topology:

Figure: Topology of a single-cell scenario.
Scenario 1: Single-cell

- 3 users are connected with a modulation rate $PHY_i = 54\text{Mbps}$...
- ...some time later a fourth user appears with $PHY_4 = 6\text{Mbps}$.
- The effective data rates are: $C_i \approx 22.4\text{Mbps}$, $i = 1, 2, 3$ and $C_4 \approx 5.1\text{Mbps}$
The throughputs converge approximately to the harmonic mean $x^*_i = 3.0 \text{Mbps}$ as predicted.
Now the throughputs converge approximately to the solution of the WNP,
\[ x^*_i = 4.2 \text{Mbps}, \ i = 1, 2, 3 \text{ and } x^*_4 = 2.1 \text{Mbps}! \]
Net throughput is increased by \( \approx 20\% \).
Scenario 2: wired-wireless network

We simulate the following topology:

\[ \text{TCP1} \quad \text{AP} \quad \text{TCP2} \]

To check the model when utilities are not the same (different RTTs).

\[ \text{PHY}_1 = 54 \text{Mbps} \quad \text{and} \quad \text{PHY}_2 = 6 \text{Mbps}. \]
Scenario 2: wired-wireless network. Results

The model predicts accurately both equilibriums. Applying MRED we obtain again almost 20% throughput increase.

Figure: Wired-wireless topology simulation. Left: original allocation. Right: MRED algorithm.
Scenario 3: tree topology

We simulate the topology:

\[\text{Access (Caccess) \rightarrow Distribution (Cdist)}\]

\[\text{Internet \rightarrow AP1 \rightarrow Distribution (Cdist) \rightarrow APn} \]

\[\text{Access (Caccess) \rightarrow APn} \]
Scenario 3: tree topology. Results

Simulation parameters:

- $c_{access} = 20 \text{Mbps}$ representing a typical access capacity.
- $c_{dist} = 100 \text{Mbps}$ (overprovisioned)
- Identical non-interfering wireless cells, $PHY_1 = PHY_3 = 54 \text{Mbps}$ and $PHY_2 = PHY_4 = 6 \text{Mbps}$.
- Each user has a single TCP connection and all connections have equal RTTs.

Plugging these values in the general NUM problem gives:

$$x_1^* = x_3^* = 6.5 \text{Mbps} \quad x_2^* = x_4^* = 3.5 \text{Mbps}$$
Scenario 3: tree topology. Results

**Figure:** Throughputs of TCP connections for a wireless access scenario with 4 users. MRED is in use.
Conclusions

- We applied the NUM framework to characterize the cross-layer interaction between the TCP transport protocol with an underlying MAC where multiple modulation rates coexist.
- We analyzed the impact of overheads in the throughput of TCP connections.
- We described the resource allocation imposed by current wireless networks in this framework, characterizing its equilibrium through a suitable NUM problem.
- We proposed an alternative resource allocation that generalized the fairness and efficiency notions of wired networks.
Conclusions

- This new resource allocation overcomes the inefficiencies found in current deployments.
- We also showed a simple mechanism to impose these more efficient equilibria in single cell scenarios and also showed possible generalizations of this procedure to more complex topologies.
- Simulations support the theoretical results.
Future work

- Determine the topologies where Multirate RED can be applied (when decentralization is possible?)
- Generalize these models to the case of IEEE 802.11n networks where:
  - Higher $PHY$ rates are expected, so the overheads become a problem.
  - Packet aggregation is used, so dropping packets must be done carefully.
- Propose new message passing mechanisms (using the RTS/CTS?) to drive the network to the proposed allocation when MRED is not sufficient.
Gracias!
Preguntas?
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