User-centric network fairness through connection level control

Andrés Ferragut    Fernando Paganini

Mathematics Applied to Telecommunications Research Group
Universidad ORT
Uruguay

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Outline

1. Motivation
2. User-centric fairness
3. Models and analysis
4. Conclusions and Future Work
Since Kelly et. al. [KMT98], resource allocation in the Internet is modelled as an utility maximization problem (NUM).

However, in current congestion control protocols, the utility represents the protocol behavior.
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Fairness is imposed on a per connection-basis.

Notion of fairness determined by the protocol (TCP).
Users get in the way...

- Users may open multiple connections...
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  - ...to push for a larger share of resources.
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- The notion of “flow rate fairness” is artificial.
- We need a user-centric notion of fairness (and decentralized ways to achieve it!).
The network is composed of links ($l$) and users have one or several routes ($r$) over these links to open their connections.

- $x_r$: rate of a single connection.
- $n_r$: number of ongoing connections.
- $\varphi_r = n_r x_r$: aggregate rate.
Some notation...

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- \(x_r\): rate of a single connection.
- \(n_r\): number of ongoing connections.
- \(\varphi_r = n_r x_r\): aggregate rate.
- \(\varphi^i = \sum_{r \in i} \varphi_r\): aggregate rate of user \(i\).
- \(R_{lr}\): the routing matrix.
- \(y_l = \sum_r R_{lr} \varphi_r\): the rate in link \(l\).
Per-connection rates $x_r$ satisfy [Sri04]:

Problem (TCP Congestion control)

For fixed $\{n_r\}$,

$$\max_{\{x_r\}} \sum_r n_r U_{TCP_r}(x_r),$$

subject to capacity constraints:

$$\sum_r R_{lr} n_r x_r \leq c_l$$

Here $U_{TCP_r}$ reflects the congestion controller.
What we want to solve...

The user centric notion of fairness is:

Problem (User Welfare)

\[
\max \sum_i U_i(\varphi^i),
\]

subject to:

\[
\sum_r R_{lr} \varphi_r \leq c_l
\]

with \( \varphi^i = \sum_{r \in i} \varphi_r \),

- \( U_i \) is a concave utility function that reflects the user preferences (or an SLA).
- Its argument reflects the total rate the user gets.
Achieving user-centric fairness

- **Goal:** Achieve the USER WELFARE optimum.
- **Constraint:** Without changing the TCP.
- **Idea:** Control the number of connections in each route.
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Possible knobs:
- Direct control of the $n_r$ (assumes user cooperation).
- Admission control of incoming connections.
- When multiple routes are available: choose the best route.
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Possible knobs:

■ Direct control of the $n_r$ (assumes user cooperation).
■ Admission control of incoming connections.
■ When multiple routes are available: choose the best route.
We would like to solve \( \max \sum_r U_i(\sum_{r \in i} \varphi_r) \).

If we can control \( \varphi_r \) we may use the primal dual dynamics:

\[
\begin{align*}
\dot{\varphi}_r &= k(U'_i(\varphi_r) - q_r) \\
\dot{p}_l &= \gamma(y_l - c_l)_{pl}^+ \\
y &= Rx, \quad q = R^T p.
\end{align*}
\]

Problem: In the multipath case, it may oscillate ([AUU58]) (the problem is not strictly concave).
Controlling the $n_r$ I

- We would like to solve $\max \sum_r U_i(\sum_{r \in i} \varphi_r)$.
- If we can control $\varphi_r$ we may use the primal dual dynamics:

$$\dot{\varphi}_r = k(U'_i(\varphi_r) - q_r - \nu \dot{q}_r)$$
$$\dot{p}_l = \gamma(y_l - c_l)^+$$
$$y = Rx, \ q = R^T p.$$ 

- **Problem:** In the multipath case, it may oscillate ([AUU58]) (the problem is not strictly concave).
- **Our solution:** Old control control trick, add a predictive term in the price.

**Theorem**

*The preceding control law is globally asymptotically stable (details in the paper).*
Controlling the $n_r$ II

- We cannot control $\varphi_r$ directly (partially controlled by TCP).
- **Idea:** Find a control law for $n_r$ such that the $\varphi_r = n_r x_r$ follow the preceding equations.

**Solution:** choose $n_r$ to satisfy

$$\dot{n}_r = n_r[k(U'_i(\varphi_r) - q_r - \nu \dot{q}_r) + \dot{x}_r/x_r]$$

Note the same price is used to control TCP and $n_r$. 
Controlling the $n_r$ III

Theorem

If $n_r$ follows:

$$\dot{n}_r = n_r[k(U'_i(\varphi_r) - q_r - \nu \dot{q}_r) + \dot{x}_r/x_r]$$

the system is globally convergent to the equilibrium of the User Welfare Problem.
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**Remark:** The derivative terms are harder to estimate correctly.
Controlling the \( n_r \) III

**Theorem**

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\dot{n}_r = n_r[k(U'_i(\varphi_r) - q_r - \nu \dot{q}_r) + \dot{x}_r/x_r]
\]

the system is globally convergent to the equilibrium of the User Welfare Problem.

- **Remark:** The derivative terms are harder to estimate correctly.
- The simpler dynamics:

\[
\dot{n}_r = kn_r(U'_i(\varphi_r) - q_r)
\]

seems to perform fine on simulations.

- We implemented this cooperative control in the ns-2 simulator.
Scenario 1: Controlling the number of connections.

User 1

C1 = 4 Mbps

User 2

C2 = 10 Mbps

C3 = 6 Mbps

Topology simulated in Scenario 1.

Optimal allocation:

\[ \varphi^1 = \varphi^2 = 10 \text{Mbps} \]

Results for Scenario 1
Utility based admission control:

- **Problem:** Users may choose not to control their connections.
- Can we do admission control to impose fairness?

**Utility Based Admission Control**

Apply the following rule:

\[
\text{If } U'_i(\varphi^i) > q_r \rightarrow \text{admit connection.}
\]

\[
\text{If } U'_i(\varphi^i) \leq q_r \rightarrow \text{discard connection.}
\]

- Compare the *user* demand curve with current route price.
- Admit connection when price is sufficiently low (route not congested).

Which notion of fairness is imposed by this rule?
Scenario 2: Fairness via admission control.

User Welfare max-min allocation:

\[ \varphi^1 = 5\text{Mbps} \]

\[ \varphi^2 = \varphi^3 = 3\text{Mbps}. \]
Scenario 2: Fairness via admission control.

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Scenario 2: Fairness via admission control.

User Welfare max-min allocation:

$\varphi^1 = 5 \text{Mbps}$

$\varphi^2 = \varphi^3 = 3 \text{Mbps}$.

Admission control is imposing the User Welfare notion of fairness.

What happens when not all users are congesting the network?
Scenario 2: Fairness via admission control.

Assume now that User 2 only demands 1Mbps on average.

A reasonable allocation would be:

\[
\begin{align*}
\varphi^1 &= 4\text{Mbps} \\
\varphi^2 &= 1\text{Mbps} \\
\varphi^3 &= 4\text{Mbps}.
\end{align*}
\]
Scenario 2: Fairness via admission control.

C1=8Mbps C2=6Mbps

User 3

User 1

User 2

Assume now that User 2 only demands 1Mbps on average.

A reasonable allocation would be:

\[ \varphi^1 = 4\text{Mbps} \]
\[ \varphi^2 = 1\text{Mbps} \]
\[ \varphi^3 = 4\text{Mbps}. \]

Note that User 2 is protected by admission control.
Modelling admission control

- Assume users start connections as a Poisson Process of intensity $\lambda_r$ on route $r$.
- Each connection brings an exponentially distributed job, with mean $1/\mu_r$. 
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Each connection brings an exponentially distributed job, with mean $1/\mu_r$.

This is similar to [dVLK99, BM01] connection level models.

The network is stable iff $\sum_{r \in l} \lambda_r / \mu_r < c_l$ (all users are satisfied).
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The network is stable iff $\sum_{r \in \mathcal{L}} \lambda_r / \mu_r < c_l$ (all users are satisfied).

If the network is not stable, through a fluid limit analysis we show that admission control solves:

**Problem (Saturated USER WELFARE)**

$$\max \sum_i U_i(\varphi^i)$$

subject to $R\varphi \leq c$, and $\varphi_r \leq \lambda_r / \mu_r$ for each $r$. 
Same as Scenario 1, but now with UBAC instead of cooperating users. The network is overloaded.

Optimal allocation:
\[ \varphi^1 = \varphi^2 = 10\text{Mbps}. \]
Back to Scenario 1: Adm. control in multiple routes

Same as Scenario 1, but now with UBAC instead of cooperating users. The network is overloaded.

Optimal allocation:
\[ \varphi^1 = \varphi^2 = 10\text{Mbps}. \]

We can impose the same notion of fairness through UBAC.
Combining admission control and routing

- If we can choose the route of a connection, we can combine admission control with routing.
- In the paper, we partially characterize the stability region of the multipath connection level model, with single-path connections (generalizes [dVLK99, BM01], similar to [HSH+06]).
- We generalize the admission control rule:

\[
\text{UBAC with routing}
\]

\[
\text{Admit new connection if } \min_{r \in i} q_r < U'_i(\varphi^i)
\]

If admitted: route through cheapest path.

- We have partial results showing that it imposes a Multipath User Welfare allocation.
Conclusions and future work

We studied the issues of stability and fairness created by the ability to open multiple TCP connections.

- **Contributions:**
  - Control laws for the number of connections to achieve User-Centric Fairness.
  - Utility-based Admission Control for stability and user fairness.
  - Price-based routing of connections and combination with admission control.

- **Open questions:**
  - Stability under routing: we have partial results.
  - Global stability for admission control.
  - Deployable control mechanisms for the real Internet. In particular, enabling edge routers to enforce utility-based SLAs.
Thank you!
Questions?
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Contact: ferragut@ort.edu.uy
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