INADEQUACY OF THE QUEUE-BASED MAX-WEIGHT OPTIMAL SCHEDULER ON WIRELESS LINKS WITH TCP SOURCES

Alfredo Todini, Andrea Baiocchi and Daniele Venturi
Infocom Department, University of Rome “Sapienza”, Rome, Italy

Introduction and Motivation

The interaction between wireless optimized scheduling algorithms and TCP congestion control has adverse effects on performance:

- bandwidth fluctuations negatively affect the performance of TCP;
- capacity variations typical of wireless channels are amplified by *opportunistic* schedulers.

We investigate the impact of various wireless scheduling techniques on the performance of TCP.

System Model

- K TCP connections from wired sources to wireless users connected to a single Base Station (BS);
- one queue per user in the BS;
- long-lived TCP connections, in saturation;
- OFDMA multiple access scheme.

Scheduling Algorithms

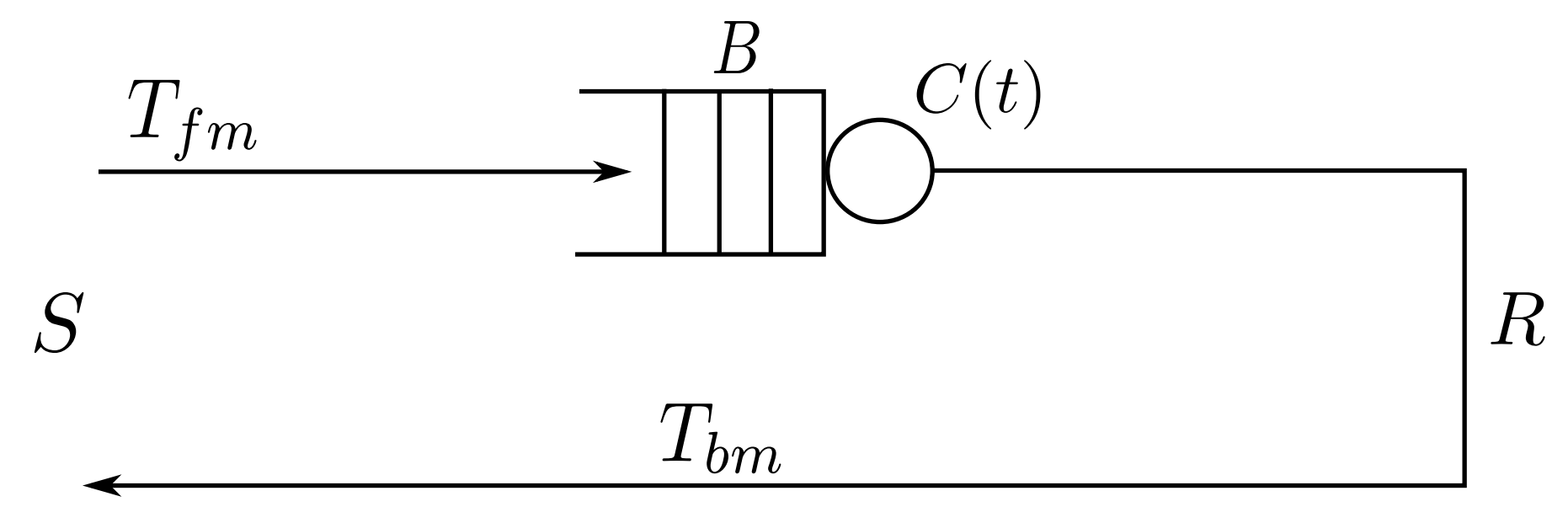
The time axis is divided into frames. In each frame, of duration T_a, we allocate subcarriers to users by maximizing a weighted sum of the transmission rates of the users, given a total power budget P_{max}.

$$\begin{aligned}
&\max_{\boldsymbol{\rho},\mathbf{p}} \sum_{k=1}^{K} w_k \sum_{n=1}^{N} \rho_{k,n} r_{k,n}\\
&\sum_{k=1}^{K}\sum_{n=1}^{N} \rho_{k,n} p_{k,n} \le P_{max}\\
&\sum_{k=1}^{K} \rho_{k,n} \le 1 \quad n = 1,\dots,N\\
&\rho_{k,n} \in \{0,1\}\,, \quad k = 1,\dots,K, \quad n = 1,\dots,N
\end{aligned}$$

where $r_{k,n}$ is the maximum rate at which the BS can reliably transmit to user k on subcarrier n at power $p_{k,n}$. The choice of the weights w_k defines a scheduling policy:

- **Queue-Based Max-Weight (QBMW) scheduler**: $w_k = Q_k$ (the queue length of user k). This is a *throughput optimal* scheduler when used with non-congestion controlled sources;
- **Proportional Fair (PF) scheduler**: $w_k(\ell) = 1/\Lambda_k(\ell)$, where $\Lambda_k(\ell)$ is the time average of the rate achieved by the k-th user;
- **Queue-Age (QA) scheduler**: $w_k(\ell) = \lceil D_k^*(\ell)/T_a \rceil$, where $D_k^*(\ell)$ is the delay of the oldest packet stored in user k's queue at the beginning of the ℓ-th allocation frame.

TCP Fluid Model



- Single, variable capacity bottleneck link.
- Buffer of size B (packets).

The model is described by continuous-time differential equations, which are discretized by sampling time.

$$\begin{aligned}
Q(t_{i+1}) &= \min\{B, Q(t_i) + X(t_i) - U(t_i)\}\\
U(t_i) &= \min\{C(t_i), Q(t_i) + X(t_i)\}
\end{aligned}$$

In the time interval $[t_i, t_{i+1})$:

- an amount of fluid $X(t_i)$ enters the buffer;
- an amount of fluid $U(t_i)$ leaves the buffer;
- a capacity $C(t_i)$ is available.

The model is based on macro-states, representing phases of the congestion control.
Slow Start (SS):

$$\begin{aligned}
W(t_{i+1}) &= W(t_i) + U(t_{i-m})\\
X(t_i) &= 2U(t_{i-m})
\end{aligned}$$

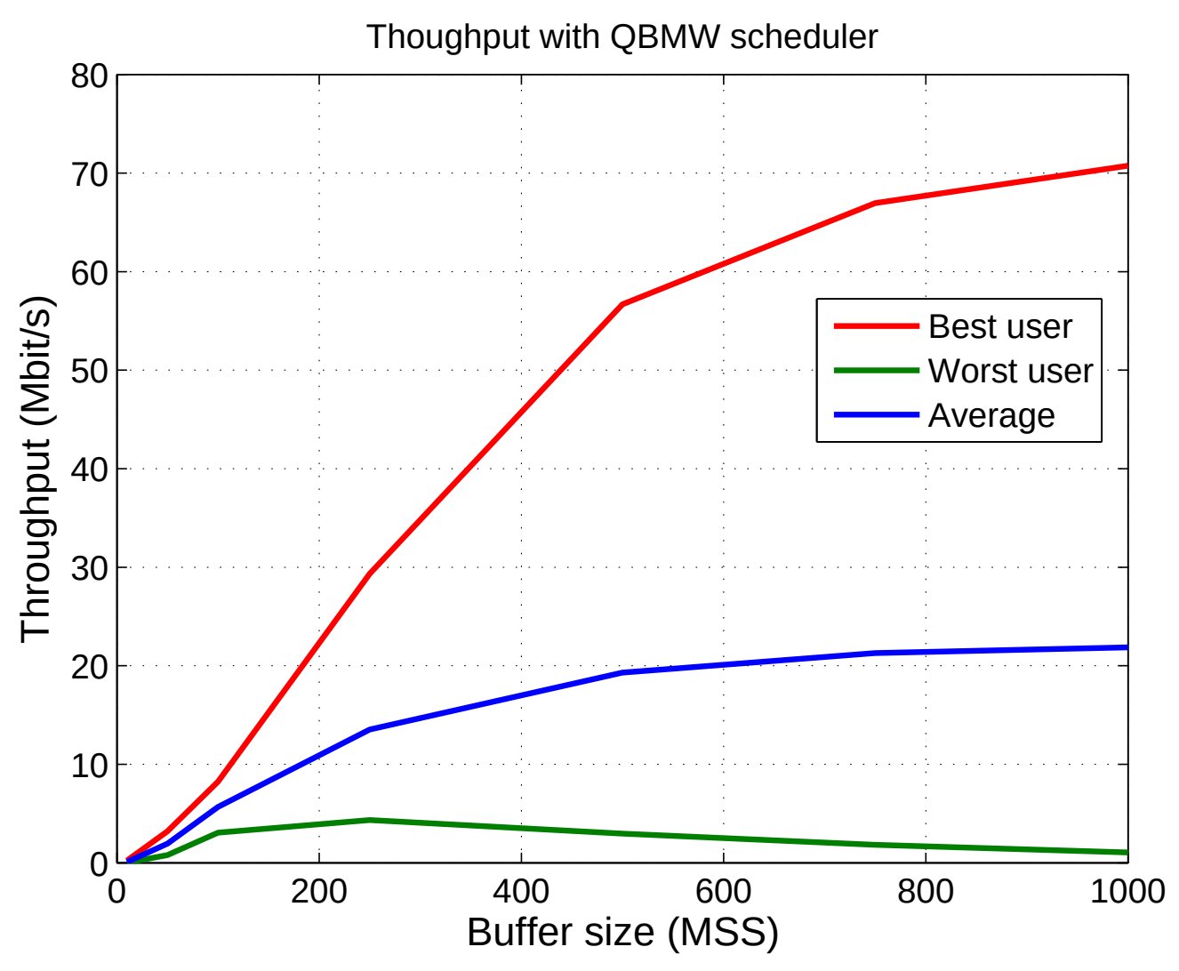
When $W(t_i) \ge$ *ssthresh* the state switches to Congestion Avoidance (CA) and

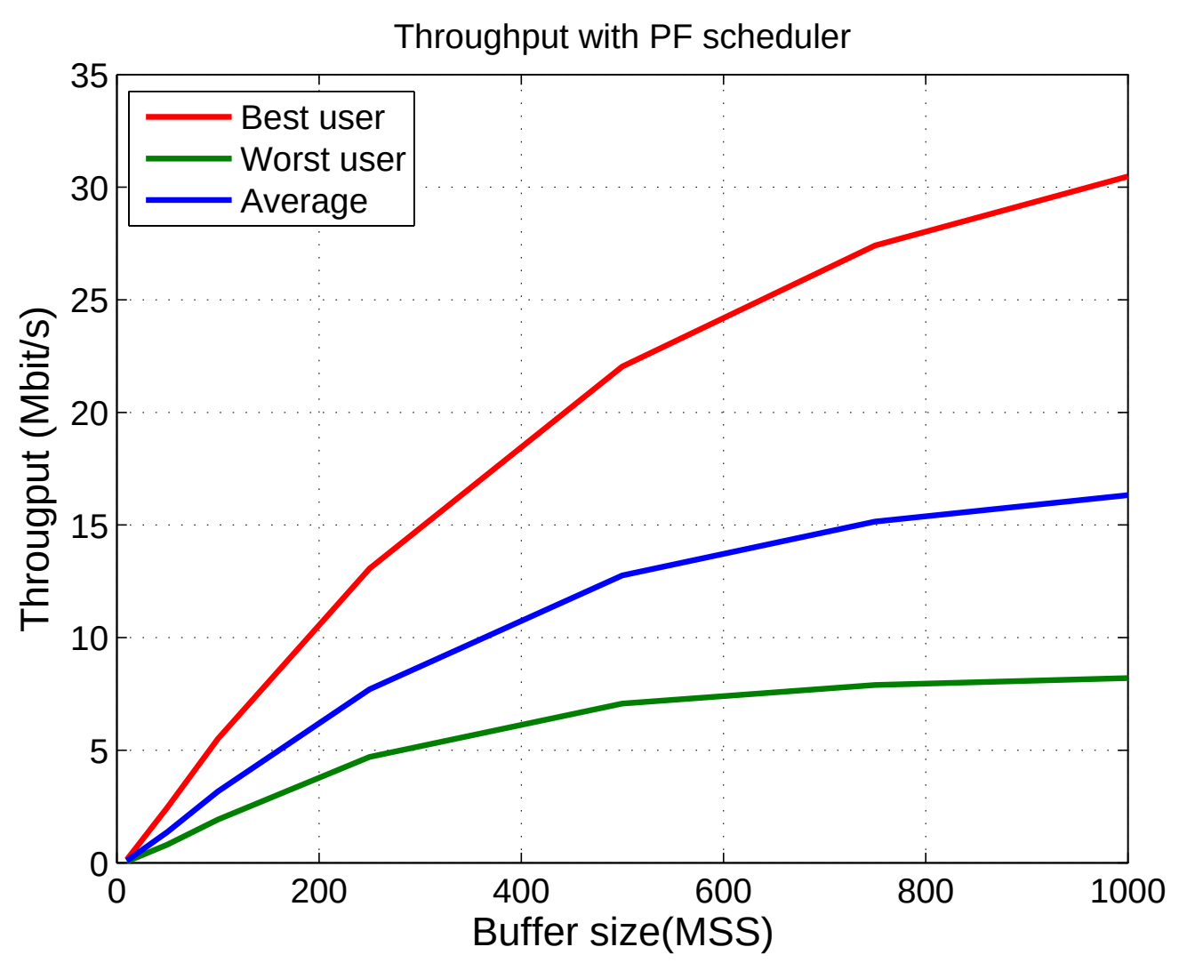
$$\begin{aligned}
W(t_{i+1}) &= W(t_i) + \frac{U(t_{i-m})}{W(t_i)}\\
X(t_i) &= U(t_{i-m}) + \frac{U(t_{i-m})}{W(t_i)}
\end{aligned}$$

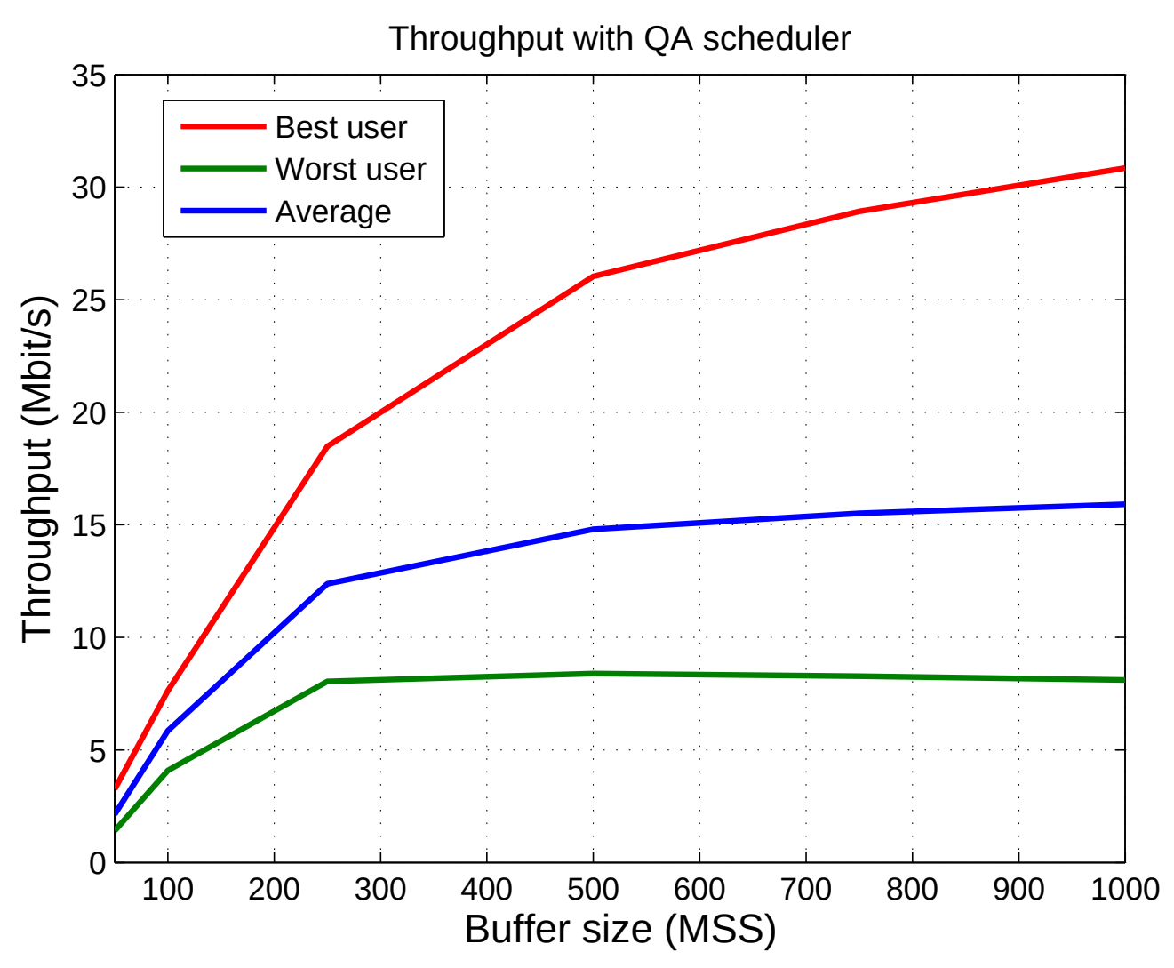
After a loss the state changes to Loss Unaware (LU) (the time needed for the packet loss event to be detected by the TCP source); after the Fast Retransmit (FRx) and Fast Recovery (FRc) states, the whole pending window of fluid has left the pipe. At that point we set $W(t_i) = (1-b)W_f$ and *ssthresh* $\leftarrow (1-b)\cdot$ *ssthresh* and CA is resumed.

Simulation Results

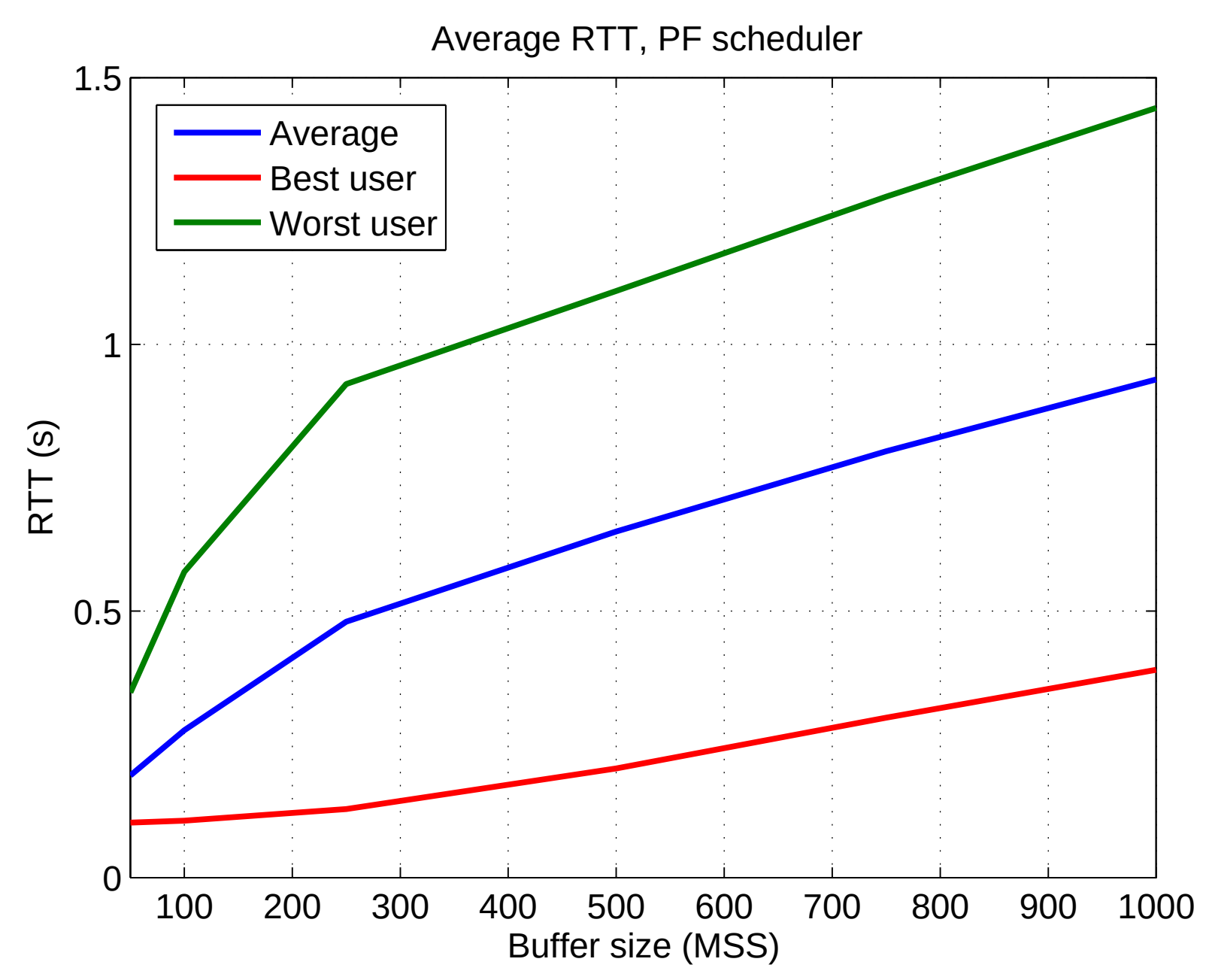
$K = 5$ wired TCP sources send traffic to K mobile TCP sink nodes. Cell radius $R_0 = 1500\ m$. The wireless bandwidth is $N\Delta_f = 20MHz$. The channel is frequency-selective Rayleigh fading with lognormal shadowing. The overall bandwidth is divided into $N = 16$ orthogonal subchannels. Radio resources are allocated for a frame of duration $T_a = 10\ ms$. TCP sources generate 1024-byte long packets. The basic RTT of the TCP connection is $T_m = 100\ ms$. The TCP window size is assumed to be unlimited, thus ensuring that TCP is never window limited by the TCP source. The Maximum Segment Size (MSS) is assumed to be 1024 *bytes*.

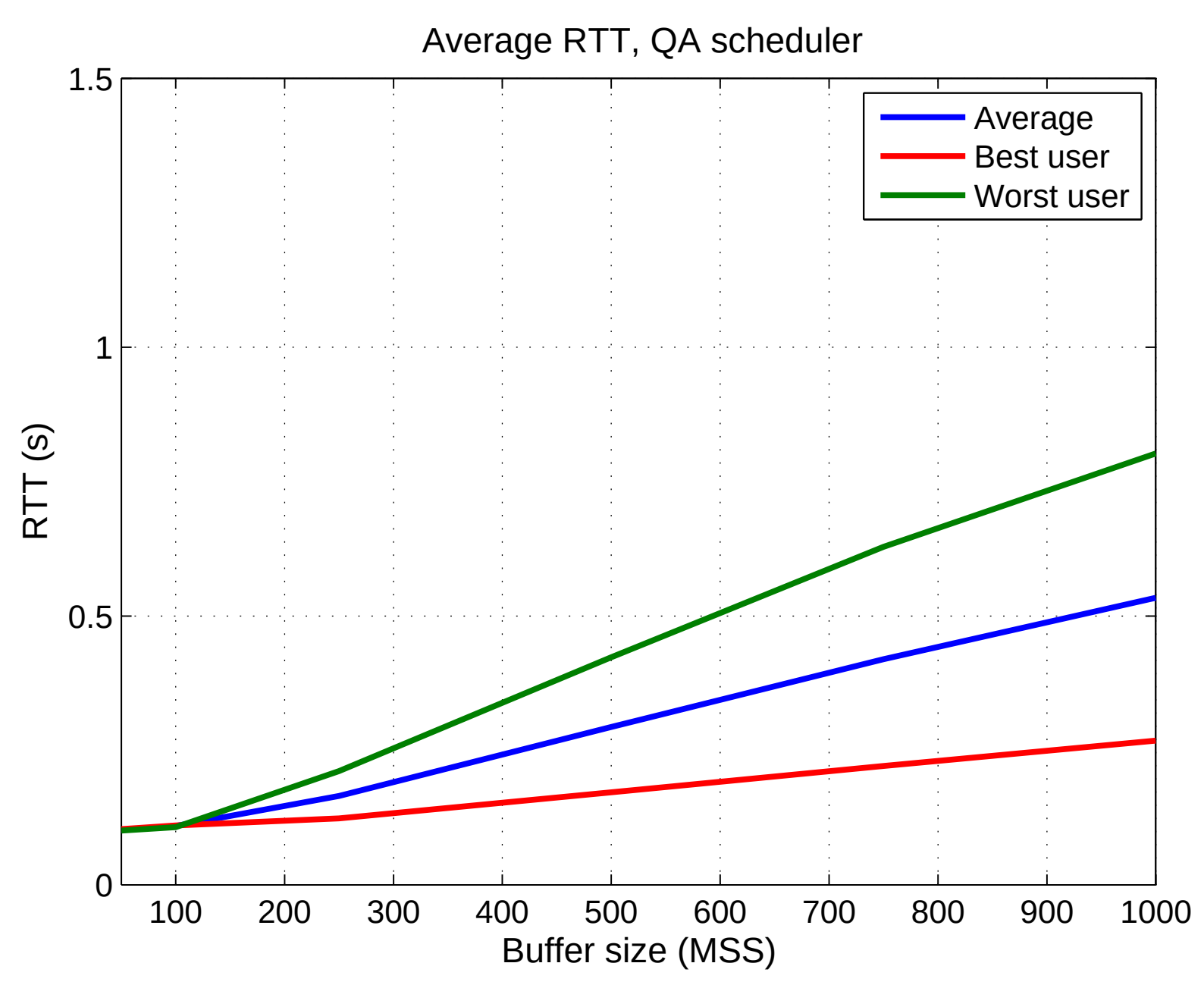

Thoughput with QBMW scheduler


Throughput with PF scheduler


Throughput with QA scheduler

The QBMW scheduler does not achieve a fair allocation of resources; the interaction with the TCP congestion control results in a very low throughput achieved by the most disadvantaged user. The PF and QA schedulers are able to achieve a fairer resource sharing among users. Note that, with all scheduling policies, throughput increases with the buffer size B and saturates only for large values of B. The QA scheduler achieves throughput values close to saturation for much smaller buffer sizes than the PF scheduler, thus it is better suited at handling TCP flows.


Average RTT, PF scheduler


Average RTT, QA scheduler

With the QA scheduler packets experience a markedly lower latency than with the PF scheduler; in fact, the QA policy results in shorter average queue lengths and thus shorter delays.

Conclusions

The Queue Based Max-Weight scheduling policy, known to be throughput-optimal under stationary unregulated traffic sources, leads to a very unfair outcome when traffic is generated by TCP sources.
In contrast, other scheduling policies, such as the Proportional Fair (PF) scheduler do not show this pathologic behavior. In particular, we introduced the Queue Age (QA) scheduling policy, which takes into account the delay of the oldest packet stored in the wireless buffer of each user; compared to the PF scheduler, the QA algorithm manages to achieve shorter packet delays and a higher throughput efficiency for smaller buffer sizes.