

On the buffer occupancy of an IEEE 802.11 station in a Hot-Spot

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Abstract— In this letter we evaluate analytically the average occupancy of the transmission buffer of a 802.11 station (STA). The station belongs to a Wi-Fi Hot-Spot and exchanges data with a fixed host. The data exchange is regulated by the Transmission Control Protocol (TCP).

The research interest is motivated by the fact that several papers assume that in these conditions the STA buffer is nearly empty. On the contrary, we prove that this assumption may be wrong and discuss the consequences of this fact.

We test the proposed model by means of ns2 simulation, ascertain its accuracy, and highlight its limits.

Index Terms— 802.11, TCP, model, buffer occupancy

I. INTRODUCTION

We consider a Wi-Fi Hot-Spot where M stations (i.e., terminals) upload and download files to/from a fixed host by means of TCP. We analyze the average occupancy of the transmission buffer of a WLAN station (STA). The motivation of this work lies in the fact that several papers analyzing TCP performance in this environment (e.g., [1][2][3]) assume that the transmission buffer of a STA is nearly empty. Thus, the buffer occupancy of the STA is considered negligible with respect to the occupancy of the Access Point (AP) buffer located on the wireless interface. We name this assumption the *empty buffer conjecture*. The *empty buffer conjecture* strongly simplifies the modeling of the TCP send-rate. In fact, under this assumption, the delay in the WLAN is only due to packet queuing in the AP transmission buffer and packet loss occurs only in the AP. As a consequence, all TCP connections experience the same delay and packet loss probability.

However, we tested the *empty buffer conjecture* by means of ns2 simulations ⁽¹⁾ and observed a rather surprising result: in some simulation scenarios the *empty buffer conjecture* is not valid for some STAs.

Given these results, we felt the urge to better understand what is going on and to derive an analytical model of the system, so that fellow researchers can exploit the *empty buffer conjecture* only when it is right to do so. We also verified that the references quoted above ([1][2][3]) assume working environments in which the *empty buffer conjecture* is indeed valid.

II. STA BUFFER MODEL

In this section, we derive the analytical model of the average occupancy of the STA buffer. The reference scenario consists of a set of STAs having TCP connections with fixed hosts. The wireless-wired bridging is performed by an AP.

A. Assumptions and model limits

To make the model easily tractable, we make some simplifying assumptions, reported in Table I. Let us now discuss these assumptions and the ensuing model limits ⁽²⁾.

Assumption a1 means that the wireless part is the bottleneck. Neglecting the packet loss in the wired part seems reasonable, as loss phenomena mainly occur in the wireless part. On the contrary, the delay suffered in the wired part can not be always neglected. Our basic model exploits this assumption; however in this paper we also say how to modify the model to take into account the wired-part delay.

Assumptions a2 is reasonable, since the operative system of a wireless host usually allocates a large amount of memory to its network interfaces (e.g. 1000 packets).

As regards assumption a3, the Reno version is the most widely deployed on current operative systems. So this assumption is almost always valid. Instead, when STAs use different operative systems or when users change the default configuration of the operative system the maximum congestion windows may differ. As in the case of assumption a2, we take a3 for granted to keep the basic model simple, but we also say how to modify it to account for different maximum TCP congestion windows.

¹ We make the same assessment also by means of a real test-bed made up of three laptops (with a DLINK DWL-G122 wireless adapter), of a Cisco Aironet AP and of a fixed server connected to the AP with Fast Ethernet. The test-bed results are consistent with the simulations, with small differences, likely due to different implementations of the 802.11 backoff algorithm in the STA and in the AP [5].

² We will make other three assumptions later on in the body of the paper, because they can be better understood only after introducing some propaedeutic concepts.

Assumption a4 is the major model limit. With it, we assume that all the TCP connections start and reach a steady-state behavior. In [4] we show that this assumption is not always true. As a matter of fact, in case of heavy losses, some TCP connections may be completely starved. We are not able to capture this critical-starvation phenomenon; thus, our model is valid when the loss probability is such that critical starvation does not occur. When critical starvation does occur, the model still gives correct results, if it is possible to give as inputs to the model the number of not-starved TCP connections.

Assumption a5 is quite reasonable, as the AP is the network bottleneck.

Assumption a6 saves us from evaluating the average value of the occupancy of the AP buffer, by assuming a full buffer occupancy, when losses can occur. In the no-loss case, this assumption is not necessary. The assumption is quite true as TCP flows tend to saturate the AP buffer, being this device the network bottleneck. The higher the number of connections the more verified a6 is.

As regards assumption a7, in practice, backoff procedures do not succeed in perfectly sharing the channel capacity on a per-packet basis (due to collisions and idle times). This leads to an approximation of the real performance of the system, which we will assess via simulations.

B. STA buffer model

All the following analysis is based on the definition of *round*, which is the time interval needed to send out all the packets buffered at the AP wireless interface since the start of the round itself. The i -th round start at time t_i .

To derive the model, first we analyze a *lossless* AP buffer, then we analyze a *lossy* AP buffer and, finally, we combine the two treatments, obtaining a unified result. A sufficient condition for the AP buffer to be *lossless* [1] is that the sum of the maximum congestion windows of all active TCP connections is smaller than the AP buffer size:

$$\sum_{i=1}^M (Ndw_i + Nup_i) W \leq B \quad (1)$$

where Ndw_i (Nup_i) is the number of downstream (upstream) connections of the i -th STA, W is the maximum TCP congestion window (in packets), B is the size of AP buffer (in packets) and M is the number of STAs.

1) *Lossless AP buffer*

Let us consider a generic STA buffer during a generic round k (i.e., the round that starts at time t_k) and assume that at time t_k the system has reached the steady state. In these conditions all TCP connections fully open their congestion windows. It follows that, when a TCP agent (sink/source) of a STA receives a packet from the AP (segment/ACK), coming from the fixed host, it generates a packet directed to the fixed host (ACK/segment) and queues it in the STA buffer. As a consequence, during the k -th round the number of packets loaded in the STA buffer is equal to the number of packets received from the AP.

In the same round, the number of packets that can leave the STA buffer is equal to the number of packets emitted by the AP, since the MAC layer assures the same transmission opportunities to all backlogged wireless interfaces. If we assume that during a round packet emissions and transmissions can be approximated with a fluid flow behavior, we can write the occupancy $Q_i(t_{k+1})$ of the STA buffer at the end of round k (i.e., at the start of round $k+1$) as:

$$Q_i(t_{k+1}) = \max\{0, Q_i(t_k) + Q_{ap}(t_k) \cdot P_{own_i}(t_k) - Q_{ap}(t_k)\} \quad (2)$$

where $Q_{ap}(t_k)$ is the number of packets in the AP buffer at the start of the k -th round and $P_{own_i}(t_k)$ is the probability that at the start of k -th round a packet stored in the AP belongs to a connection of the i -th STA. Note that $Q_{ap}(t_k) P_{own_i}(t_k)$ is the number of packets transmitted by the AP to the i -th STA and $Q_{ap}(t_k)$ is also equal to the number of packets leaving the STA buffer during the k -th round, since the STA has the same transmission opportunities of the AP. The *max* operation accounts for the obvious fact that the buffer occupancy can not be less than zero.

In our scenario the number of active STAs is greater than one (i.e., $M > 1$). It follows that the AP has to send packets to more than one STA and that the steady-state values of $P_{own_i}(t_k)$ is strictly less than one. As a consequence, Eq. (2) decreases as time increases and the average value of the STA buffer occupancy Q_i is equal to zero:

$$E[Q_i(t_k)] = Q_i = 0 \quad (3)$$

We can conclude that the *empty buffer conjecture* is indeed verified in all WLAN scenarios in which the

AP buffer is lossless⁽³⁾.

2) *Lossy AP buffer*

This case differs from the previous one in the following aspects:

- i) as regards downstream connections, the loss of a segment in the AP buffer reduces the TCP congestion window. Hence, the congestion window of a downstream connection is no more constant, as in the *lossless* case, but it depends on the packet loss probability of the AP buffer;
- ii) as regards upstream connections, the loss of ACKs in the AP buffer implies that, when a TCP sink located in a STA receives an ACK after a sequence of ACK losses, the TCP sink sends out a burst of TCP segments (given the fact that ACKs are cumulative). The size of this burst is equal to the number of segments cumulatively acknowledged by the received ACK. It follows that the STA may queue in its buffer more than one packet for each received ACK.

Let us first consider the downstream connections of a generic STA. Every time a segment of a downstream connection is received by a TCP sink of a STA, the TCP sink sends out the relevant ACK. This means that the STA queues a packet in the buffer at each packet reception. If we assume that, during a round, the packet emissions and transmissions can be approximated with a fluid flow behavior, we can write the number of packets $Qdw_i(t_k)$ of downstream connections stored in the buffer of the i -th STA, at the end of round k (i.e., at the start of round $k+1$) as:

$$Qdw_i(t_{k+1}) = \max\{0, Qdw_i(t_k) + Pown_dw_i(t_k) \cdot B - \chi dw_i(t_k)\} \quad (4)$$

where $Pown_dw_i(t_k)$ is the probability that a packet transmitted on the wireless interface by the AP during the k -th round belongs to a downstream connections of the i -th STA and $\chi dw_i(t_k)$ is the number of downstream packets leaving the STA buffer during the k -th round. We also remind that in the *lossy* case, according to assumption a6, the AP buffer is always full and thus in each *round* the AP transmits B packets, therefore $Pown_dw_i(t_k) \cdot B$ is the number of downstream packets transmitted by the AP to the i -th STA⁽⁴⁾.

Let us now consider the upstream connections of a generic STA. We remind that, given assumption a4,

³ When the TCP receiver uses the delayed-ack mechanism, queuing phenomena may occur even in the lossless case. As an example, with upstream connections only and delayed-acks, the term $Qap(t_k) Pown(t_k)$ in Eq. (2) should be corrected as $2 \cdot Qap(t_k) Pown(t_k)$, since the reception of an ACK generates two TCP segments. As a consequence queuing phenomena on the STA buffer show up when $Pown(t_k) \geq 0.5$.

the congestion window of upstream connections is equal to its maximum value, W . It follows that the overall number of packets in fly is equal to $Nup_i W$ ⁽⁵⁾. Given assumption a1, these packets can be in the AP buffer or in the STA buffer⁽⁶⁾ or they are lost at the AP buffer. Packets within the STA buffer are TCP segments, whereas packets lost or packets in the AP buffer are ACKs. This implies that, at the start of round k , the number of in-fly ACKs of the i -th STA is equal to $Nup_i W - Qup_i(t_k)$, where $Qup_i(t_k)$ is the number of upstream packets stored in the i -th STA buffer at time t_k .

Given the fact that ACKs are cumulative, at the end of round k , $Nup_i W - Qup_i(t_k)$ segments will be acked by the AP; as a consequence, the TCP senders will queue in the STA buffer the same number of segments. It follows that, at the end of round k , the number of packets of upstream connections contained in the buffer of the i -th STA can be written as:

$$Qup_i(t_{k+1}) = \max\{0, Qup_i(t_k) + (Nup_i \cdot W - Qup_i(t_k)) - \chi up_i(t_k)\} = \max\{0, Nup_i \cdot W - \chi up_i(t_k)\} \quad (5)$$

where $\chi up_i(t_k)$ is the number of upstream packets leaving the STA buffer during the k -th round.

If we assume that the involved random processes are stationary, by taking the average of both members of Eqs. (4) and (5) and by approximating $E[\max(X,Y)]$ with $\max(E[X],E[Y])$ ⁽⁷⁾ we obtain an approximation of the average number Qdw_i (Qup_i) of downstream (upstream) packets stored in the buffer of the i -th STA:

$$Qdw_i = \max\{0, Qdw_i + Pown_dw_i \cdot B - \chi dw_i\} \quad (6)$$

$$Qup_i = \max\{0, Nup_i \cdot W - \chi up_i\} \quad (7)$$

where $Pown_dw_i$ is the steady-state probability that a packet transmitted by the AP on the wireless interface belongs to a downstream connections of the i -th STA and χdw_i (χup_i) is the average number of downstream (upstream) packets leaving the STA buffer during a round.

We now calculate the average occupancy of the STA buffer $Q_i = Qdw_i + Qup_i$. Unfortunately, the *max* operator in Eqs. (6) and (7) makes difficult this evaluation. For this reason, we first evaluate Q_i when it is

⁴ When the TCP receiver uses the delayed-ack mechanism, the term $Pown_dw_i(t_k)B$ in Eq. (4) should be corrected as $0.5Pown_dw_i(t_k)B$, since the reception of two segments generates an ACK only. We also note that Eq. (5) remains valid also in case of delayed-acks.

⁵ If the connections do not have the same maximum congestion window, then the number of packets in fly is the sum of the congestion windows of all connections. The same result obviously applies also for downstream connections (see below).

⁶ If the RTT of the fixed network is not negligible, as assumed in assumption 1 in this paper, then we also have packets in the fixed network's pipe. In that case, we must modify our derivation as follows. By denoting with X the average number of packets contained in the fixed network's pipe, the parameter B in the equations that follow must be substituted with an equivalent buffer size $B' = B + X$.

⁷ We note that this approximation results in an underestimation of STA buffer occupancy, which decreases as the STA buffer occupancy increases.

greater than zero and then we take into consideration what happens when the STA buffer is empty.

When $Q_i > 0$ Eqs. (6) and (7) may be particularized in three different ways, depending on the traffic scenarios: i) when there are only downstream connections Eq. (7) becomes $Q_{up_i} = 0$ while the *max* operator can be neglected in Eq. (6), since $Q_i = Q_{dw_i} > 0$; ii) when there are only upstream connections Eq. (6) becomes $Q_{dw_i} = 0$ while the *max* operator can be neglected in Eq. (7); iii) when there are both upstream and downstream connections, the *max* operators of Eqs. (6) and (7) may be neglected, since both upstream and downstream connections have packets in the *shared* STA buffer. In the following we derive the value of Q_i in the latter case. Nevertheless, it is easy to verify that the formula of Q_i that we obtain in this case (the following Eq. (12)) will be valid also for the two cases of unidirectional data traffic.

The parameter χ_{up_i} can be evaluated as the average number of packets leaving the STA buffer during a *round* (i.e., B) multiplied by the probability that such packets belong to upstream connections of the i -th STA. The latter probability is equal to the ratio between the average value of upstream packets in the STA buffer and the average value of all packets in the STA buffer. The same reasoning can be done with reference to χ_{dw_i} , thus obtaining

$$\begin{aligned}\chi_{up_i} &= \frac{Q_{up_i}}{Q_{dw_i} + Q_{up_i}} \cdot B \\ \chi_{dw_i} &= \frac{Q_{dw_i}}{Q_{dw_i} + Q_{up_i}} \cdot B\end{aligned}\tag{8}$$

By combining Eqs (6), (7) and (8) we obtain that the average value of the STA buffer Q_i when it is greater than zero can be expressed as:

$$Q_i = Q_{dw_i} + Q_{up_i} = \frac{N_{up_i} \cdot W}{(1 - P_{own_dw_i})} - B\tag{9}$$

Now we are left with the evaluation of $P_{own_dw_i}$. This probability is equal to the ratio between the number of downstream packets of the i -th STA entering the AP buffer in the unit time and the overall number of packets entering the AP buffer in the unit time. If we take as time unit the average packet delay in the AP buffer $E[D_{AP}]$ (i.e., the average duration of a round), we have:

$$P_{own_dw_i} = \frac{\frac{Ndw_i \cdot NormSendRate(p, W)}{E[D_{AP}] + E[D_i]} \cdot E[D_{AP}]}{B \cdot \left(\frac{1}{1-p}\right)} = \frac{Ndw_i \cdot NormSendRate(p, W) \cdot (1-p)}{B + Q_i} \quad (10)$$

where $E[D_i]$ is the average packet delay of the buffer of the i -th STA and $NormSendRate(p, W)$ is the number of segments emitted by a TCP connection during a RTT (i.e., $E[D_{AP}] + E[D_i]$) in presence of a segment loss probability p and with a maximum congestion window equals to W . $NormSendRate(p, W)$ is evaluated as the send-rate multiplied by the RTT; for the send-rate we use the classical expression obtained in [6] (specifically Eq. (32) of [6]) where we assume $T_0 = RTT$. As regards the second passage in Eq. (10), it is obtained by substituting the ratio $E[D_i]/E[D_{AP}]$ with the ratio Q_i/B (this is justified by the fact that the MAC layer gives the same transmission opportunity to all backlogged transmitters⁽⁸⁾).

Now, if we put in Eq. (9) the value of $P_{own_dw_i}$, as evaluated in Eq. (10), we obtain a quadratic equation in the unknown Q_i . By solving the equation we obtain two solutions: one is less than zero ($Q_i = -B$) and the other is:

$$Q_i = Nup_i \cdot W + Ndw_i \cdot NormSendRate(p, W) \cdot (1-p) - B \quad (11)$$

The last expression gives the average occupancy of the STA buffer when it is greater than zero. Thus, to account for the general case we must write:

$$Q_i = \max\{0, Nup_i \cdot W + Ndw_i \cdot NormSendRate(p, W) \cdot (1-p) - B\} \quad (12)$$

To complete the evaluation of Q_i , we need to evaluate p . By definition, p is equal to one minus the ratio between the traffic leaving the AP buffer and the traffic offered to the AP buffer:

$$p = 1 - \frac{\frac{B}{E[D_{AP}]}}{\sum_{j=1}^M \frac{Nup_j \cdot W + Ndw_j \cdot NormSendRate(p, W)}{E[D_j] + E[D_{AP}]}} \quad (13)$$

$$= 1 - \frac{B}{\sum_{j=1}^M \frac{Nup_j \cdot W + Ndw_j \cdot NormSendRate(p, W)}{1 + \frac{Q_j}{B}}}$$

If we combine the M Eqs. (12), one for each of i ($1 \leq i \leq M$), and Eq. (13) we get a set of $M+1$ equations with $M+1$ unknowns. To solve this system we resort to numerical techniques.

⁸ This is true if all stations and the AP use the same backoff procedure [5], otherwise a suitable correction factor must be introduced.

3) General case

To combine the *lossless* and *lossy* cases, we simply note that if we use Eq. (12) also in lossless case (i.e., $p=0$) we get $Q_i=0$ as given by Eq. (3). Summing up, we can consider Eq. (12) as a unique formula valid both for the *lossless* and for the *lossy* case.

Finally, we note that a rough approximation of the average buffer occupancy is given by⁽⁹⁾

$$Q_i = \max\{0, Nup_i \cdot W - B\} \quad (14)$$

In fact, when $Nup_i \cdot W - B > 0$, downstream TCP connections experience many segment losses, which choke the congestion window and reduce the number of downstream packets making them negligible [1][2][4]. Thus, queuing phenomena in the STA buffer are essentially produced by upstream connections.

We can qualitatively explain this point by observing that the transmission of a packet belonging to a *downstream* connection from the AP (i.e., a TCP segment) implies the queuing of a TCP ACK in the STA buffer, while at the same time granting a transmission opportunity to the STA; this opportunity allows the STA to empty the queued ACK. On the contrary, when the AP transmits a packet belonging to an *upstream* connection (i.e., a TCP ACK), the STA in turns gets a transmission opportunity. However, in this case, if there are losses in the AP buffer, the received ACK may confirm more than one segment belonging to an upstream connection; thus, the TCP source on the STA may generate and enqueue in the STA buffer a number of segments greater than the transmission opportunities granted to the STA.

III. MODEL ASSESSMENT THROUGH SIMULATION

We test the proposed model via ns2.31 simulation. The simulation parameters are reported in Table II; parameters not reported in this table are assigned the ns2.31 default values. The simulation scenario consists of 3 STAs having TCP connections with a fixed host. The wired-wireless bridging is performed by an AP. We run simulations for different values of the number of upstream and downstream connections on each STA. In all simulations we verified that assumption a4 holds. We consider four simulation scenarios.

1) First simulation scenario – only downstream connections

STA n.1 is loaded with a variable number of downstream connection; STAs n.2 and n.3 are loaded with

only one downstream connection. In this case, the sum of the average congestion windows of downstream connections can not be greater than the buffer space B , hence Eq. (12) returns a value of Q_i equal to zero. This conclusion can also be reached by looking at Eq. (9), considering that $N_{up_i}=0$ and applying the *max* operator.

Fig. 1 reports the average buffer occupancy of the three STAs versus the number of downstream connections on STA n.1, see curve labeled “STA n 1,2,3 sim (only downstream)”. The model results are not plotted since they are equal to zero. The simulation results are quite near to zero, as predicted by Eq. (12). In this case the *empty buffer conjecture* holds.

Thus, in this scenario, all TCP connections experience the same packet loss probability and the same round trip time. As a consequence they all enjoy the same useful data-rate (goodput): the WLAN system offers *per-flow* fairness. Therefore, the ratio between the overall goodput of STA n.1 and that of STA n.2 is equal to N_{dw1}/N_{dw2} , as depicted in Fig. 2.

2) Second simulation scenario – only upstream connections

STA n.1 is loaded with a variable number of upstream connections; STAs n.2 and n.3 are loaded with only one upstream connection.

Fig. 1 reports the average buffer occupancy of the three STAs versus the number of upstream connections on STA n.1, see curve labeled “STA n 1 sim (only upstream)” and “STA n 2,3 sim (only upstream)”. The model results, Eq. (12), for STAs n.2 and 3 are not plotted since they are equal to zero. Instead, model results are plotted for STAs n.1. In all cases model results follow quite precisely the simulation ones. In this case the *empty buffer conjecture* macroscopically fails for STA n.1. In fact, the average buffer occupancy of STA n.1 is about equal to zero up to 2 upstream connections and then increases as $N_{up1} \cdot W - B$, when the number of connections is greater than or equal to 3. The queue of STA n.1 can now be significantly greater than zero and this STA experiences a greater round trip time than the one experienced by the other two STAs. Therefore, the ratio between the overall goodput of STA n.1 and that of STA n.2 (see Fig. 2) is less than N_{up1}/N_{up2} . In this case, the WLAN system does not exhibit a *per-flow* fairness, as the *empty-buffer conjecture* would imply. This is a clear evidence of the importance

⁹ When the TCP receiver uses the delayed-ack mechanism this approximation holds true for lossy systems, since Eq. (5) applies also in the case of a delayed ACKs policy. In lossless systems it may fail, since queuing phenomena may occur. This fact highlights the need of always verifying the applicability of the empty-

of this phenomenon in real life situations, in terms of TCP performance.

3) *Third simulation scenario –upstream and downstream connections*

STA n.1 is loaded with a variable number of downstream connections and with three upstream connections; STAs n.2 and n.3 are loaded with only one downstream connection.

Fig. 3 reports the average buffer occupancy of the three STAs versus the number of downstream connections on STA n.1. The model results, Eq. (12), for STA n.2 and 3 are not plotted since they are equal to zero. Model results follow quite precisely the simulation ones. Also in this case the *empty buffer conjecture* macroscopically fails for STA n.1. The average buffer occupancy of STA n.1 slowly increases with the number of downstream connections. We can conclude that upstream connections have a greater impact on the average buffer occupancy than downstream connections.

4) *Fourth simulation scenario – only upstream with a variable RTT for STA n.1*

STA n.1 is loaded with five upstream connections characterized by a variable round trip time; STAs n.2 and n.3 are loaded with only one upstream connection whose round trip time is equal to zero.

This scenario is instrumental to validate our model also in the case of a fixed-network delay greater than zero. To this end, we have to modify the model as explained in footnote 6. Unfortunately, we are not able to evaluate analytically the number of packets of STA n.1 contained in the fixed-network pipe, thus we measure this quantity by means of simulations. The results reported in Fig. 4 show that when the RTT increases, the average occupancy of the STA buffer decreases, since the number of packets contained in the rest of the network (i.e. fixed-network pipe and AP buffer) increases.

IV. CONCLUSIONS

We can draw the following conclusions:

- i) if no packet loss occurs in the AP buffer, then the average occupancy of STA buffers is zero;
- ii) if there are only downstream connections and there are losses at the AP buffer, then the average occupancy of STA buffers is zero;
- iii) if there are only upstream connections and there are losses at the AP buffer, the average occupancy of the i -th STA buffer grows as $N_{up_i} W-B$;

- iv) when there are both upstream and downstream connections and there are losses at the AP buffer, then the average occupancy of the i -th STA buffer is the sum of two components: i) a first one due to upstream connections (and equal to $Nup_i W-B$); ii) a second (smaller) one due to downstream connections (and equal to $Ndw_i \text{ NormSendRate}(p, W) \cdot (1-p)$).

In all cases, a rough approximation of the average buffer occupancy is given by $\max\{0, Nup_i W-B\}$.

REFERENCES

- [1] S. Pilosof, R. Ramachandran, D. Raz., Y. Shavitt, S. Prasun, "Understanding TCP fairness over wireless LAN," in *Proc. IEEE INFOCOM 2003*, pp. 863-872.
- [2] W. Yi, N. Zhisheng, Z. Janfeng, "Upstream/downstream unfairness issue of TCP over wireless LANs with per-flow queueing," in *Proc. IEEE ICC 2005*, pp. 3543-3547.
- [3] C. Burmeister, U. Killat, J. Bachmann, "TCP over Rate-Adaptive WLAN - An Analytical Model and its Simulative Verification," in *Proc. IEEE WOWMOM 2006*, pp. 339-348.
- [4] N. Blefari-Melazzi; A. Detti; I. Habib; A. Ordine; S. Salsano, "TCP Fairness Issues in IEEE 802.11 Networks: Problem Analysis and Solutions Based on Rate Control," *IEEE Transactions on Wireless Communications*, vol.6, no.4, pp.1346-1355.
- [5] G. Bianchi, A. Di Stefano, C. Giaconia, L. Scalia, G. Terrazzino, I. Timirello, "Experimental Assessment of the Backoff Behavior of Commercial IEEE 802.11b Network Cards," in *Proc. IEEE INFOCOM 2007*, pp. 1181-1189.
- [6] J. Padhye, V. Firoiu, D.F. Towsley, J.F. Kurose, "Modeling TCP Reno performance: a simple model and its empirical validation," *IEEE/ACM Transactions on Networking*, Vol.8, No. 2, April 2000, pp. 133 -145.

TABLE I
ASSUMPTIONS

a1	the latency and the packet loss of the wired part are neglected
a2	the STA uplink buffer is large enough as to avoid packet loss
a3	the TCP version is Reno and all connections have the same maximum congestion window, W
a4	the packet loss probability at the AP downlink buffer is small enough that: i) packet losses do not prevent the startup of TCP connections; ii) the impact of ACKs loss on the congestion window dynamic is negligible
a5	the AP buffer is never empty
a6	if the sum of the maximum congestion windows of all active connections is greater than the AP downlink buffer, then the AP buffer is assumed as always full
a7	the MAC layer assures a perfect per-packet fair sharing among backlogged wireless interfaces

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Simulation time	1200 s
Initial delay after which measurement are performed	60 s
STA position	under the AP
Wireless MAC layer	802.11
Data rate	11 Mbps
Basic rate	1 Mbps
Queue type	DropTail
Maximum congestion window (W)	43 segments
TCP segment size (only payload)	1460 byte
Bit rate of the duplex link connecting the AP with the fixed host	10 Gbps
Propagation delay of the duplex link connecting the AP with the fixed host	0 in the first three scenarios. Variable for the connections of STA n.1 and 0 for the connections of STAs n.2,3 in the forth scenario.
Size of the wireless buffer of the AP (B)	100 packets
Size of the STA buffers	infinite

FIGURES

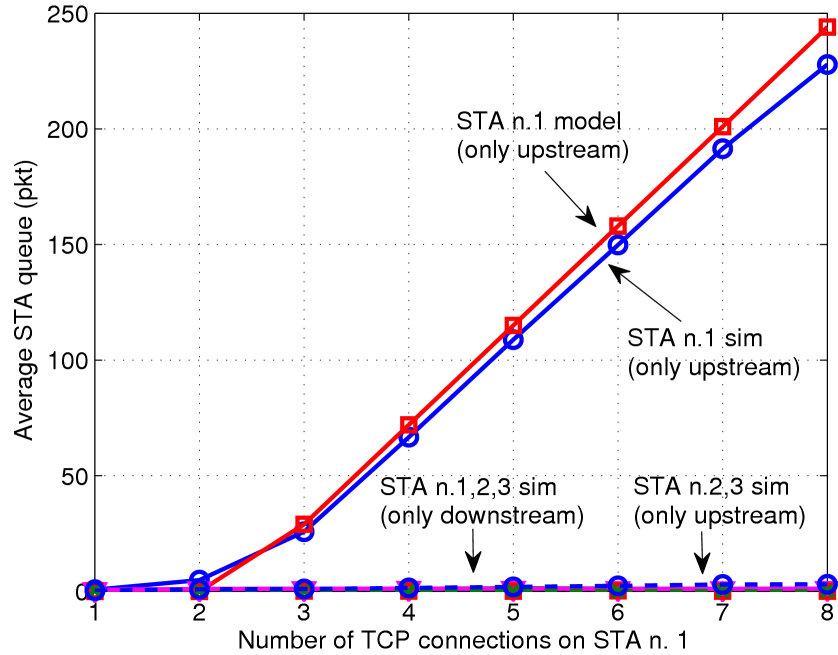


Fig. 1 – Average buffer occupancy versus the number of TCP connections on STA n. 1; STAs n. 2,3 have only one TCP connection. Simulation scenarios #1 (only downstream connections) and #2 (only upstream connections)

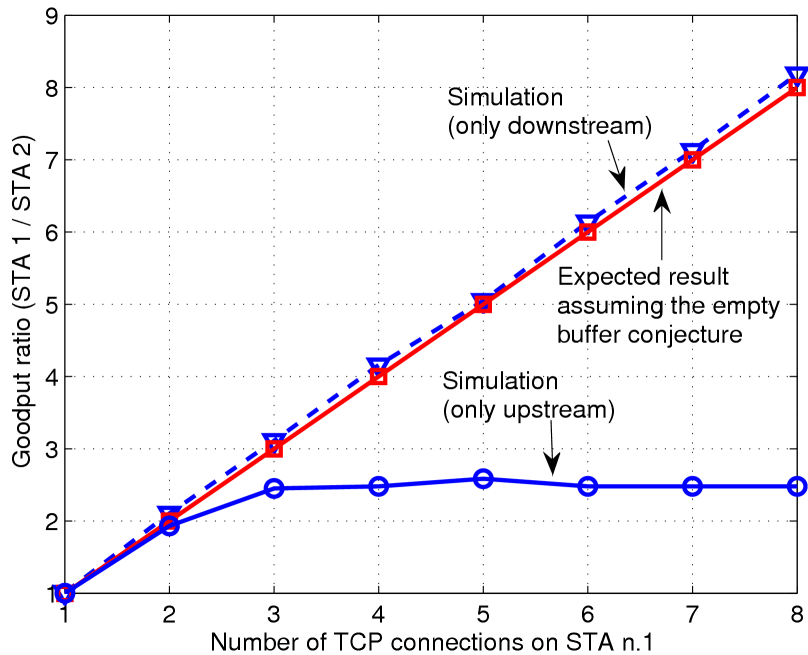


Fig. 2 – Ratio between the useful data rate (goodput) of STA n.1 and the useful data rate (goodput) of STA n.2 versus the number of TCP connections on STA n. 1; STAs n. 2,3 have only one TCP connection. Simulation scenarios #1 (only downstream connections) and #2 (only upstream connections)

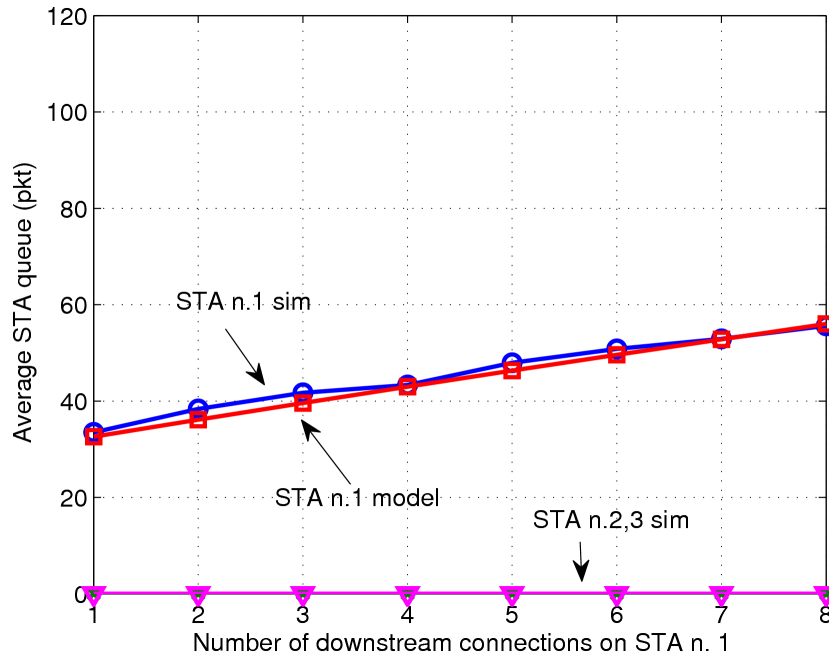


Fig. 3 – Average buffer occupancy versus the number of downstream connections on STA n.1 that has also 3 upstream connections; STAs n.2,3 have only one downstream connection

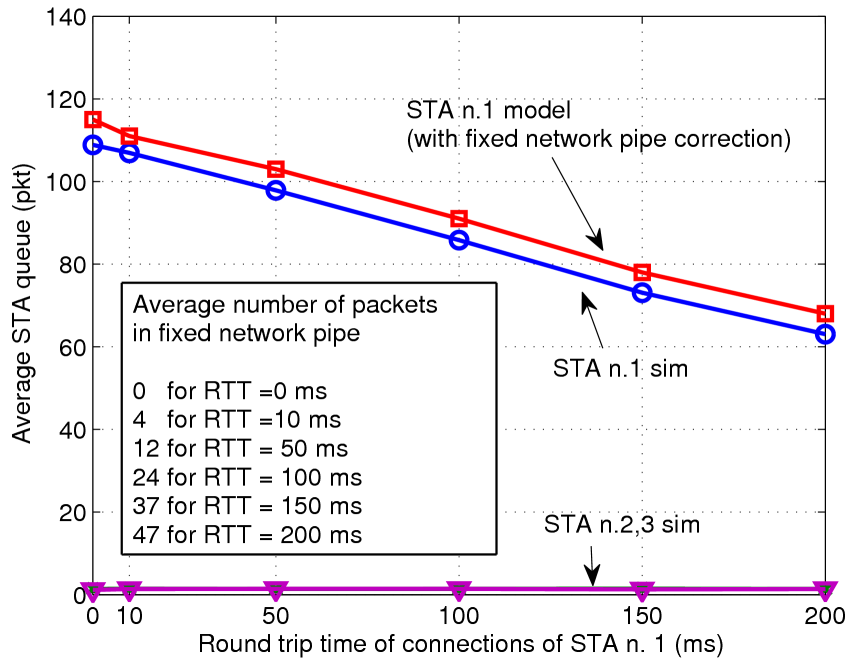


Fig. 4 – Average buffer occupancy versus the round trip time of the 5 upstream connections supported by STA n.1; STAs n. 2,3 have only one upstream connection and their round trip time equal to zero.