Enhancing TCP over HSDPA by Cross-Layer Signalling

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***Abstract*— A comprehensive performance evaluation of a cross-layer solution to increase users' downlink data rates over HSDPA is provided. The solution consists of a proxy entity between a server and the Radio Network Controller, and cross-layer signalling from the base station to the proxy. The performance of the solution is evaluated though a detailed `ns-2` simulator environment, which includes all HSDPA features, as well as some existing TCP enhancing protocols widely adopted for internet traffic over wireless links. Numerical results show that the proxy significantly increases the users' throughput, while also improving the utilization of the radio resources.**

I. INTRODUCTION

The Transmission Control Protocol (TCP) is the dominating transport protocol on the wired Internet. It is starting to play an important role also in the wireless section of the network. Third generation mobile radio systems, and enhancements such as High Speed Downlink Packet Access (HSDPA), are developed to enable wireless access to the Internet. However, large fluctuations in the delay of data delivery and in the bandwidth available to users are still present, which makes efficient use of TCP over HSDPA difficult.

Designing improvements to TCP over wireless, and predicting their performance, has been a subject of intense research in recent years [1], [2]. The main approaches proposed can be basically grouped in three categories: end-to-end solutions, physical layer solutions, and cross-layer solutions. In the following, we limit the discussion to some of the relevant contributions.

End-to-end solutions suggest interactions between the sender and the receiver in order to distinguish packet losses due to the wireless channel from those due to network congestion. One of the most popular proposals is TCP Eifel [3], which adds extra information to the acknowledgement packets to recognize spurious time outs. A major disadvantage of end-to-end approaches is the fact that existing TCP versions must be replaced.

Link-layer approaches mainly deal with the wireless interface. The Snoop protocol [4], [5] has been proposed to deal with the negative effects of Automatic Repeat reQuest ARQ over TCP. Modelling of TCP behavior over wireless links is considered in [6], [7]. In [8], the investigation concerned the forward link power allocation and rate adaptation for TCP throughput maximization in a WCDMA system. In [9] a control framework was presented to model nested loops related to the control mechanisms of TCP, ARQ and outer-loop power control for a single user in a WCDMA scenario. The negative effects of existing TCP solutions over HSDPA systems, with focus on the physical layer, have been studied in [10].

Cross-layer approaches propose to use cross-layer signalling in the protocol stack [11]. In [12], a joint optimization of the congestion window and radio power is proposed via dual decomposition, where dual variables are used as cross layer signalling. In [13], feedback from the Radio Network Controller has been included in the design of a cross-layer proxy. Cross-layer approaches seem to be the most promising way to exploit the large number of interacting factors involved in TCP over wireless. However, cross-layer signalling may cause undesired side effects [14], and may be expensive in terms of resource utilization. Sophisticated cross-layer interactions could be hard or impossible to implement in existing communication systems.

In this paper, we restrict our attention to the HSDPA system, and consider a cross-layer proxy solution for TCP over wireless links. The proxy adapts its congestion window according to a control algorithm, which is based on feedback from the Radio Network Controller about the bandwidth over the wireless interface. The stability of the controller was established in [13] and [15]. The original contribution of this paper is a performance evaluation through an accurate simulation environment which take into account all the HSDPA characteristics. The cross-layer proxy, the Reno protocol and two of the most popular TCP over wireless solutions, namely Eifel and Snoop, are included. The performance of the cross-layer proxy are evaluated with respect to these existing solutions, and as function of the communication environment, user location, HSDPA scheduler, and cross-layer signalling.

The remainder of the paper is organized as follows: in

This work was partially supported by European Commission through the Network of Excellence HYCON, contract number FP6-IST-511368, by the Swedish Foundation for Strategic Research, and by the Swedish Research Council. M. Fiorenzi and D. Girella were partially supported by Centre of Excellence DEWS of the University of L'Aquila, Italy. C. Fischione was with KTH, Stockholm, when this work was done.

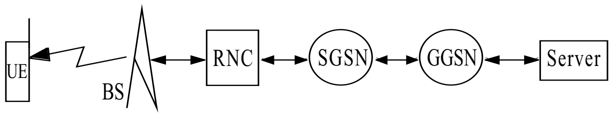

Fig. 1. Reference scenario. The RNF Proxy can be placed between the GGSN and the server, in the operator's administrative domain.

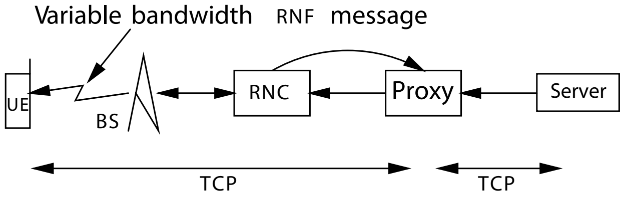

Fig. 2. Radio network feedback architecture. The mobile terminal on the left downloads a file from the server on the right, via the proxy. During the transfer, the RNC generates cross-layer RNF messages including information about the current bandwidth over the radio link, and the current RNC queue length. The proxy uses this information to adjust its window size.

section II, the system scenario is introduced. The cross-layer proxy is summarized in section III. In section IV, numerical results are presented and discussed. Finally, section V concludes the paper.

II. SYSTEM DESCRIPTION

We consider a system scenario where a mobile user UE is connected to a base station BS of a HSDPA system (see Fig. 1) The UE downloads a file from a remote server by a TCP connection. In order to increase performance of TCP over HSDPA, a cross-layer proxy is placed between the server and the Gateway GPRS Support Node (GGSN). The GGSN is then connected to the Serving GPRS Support Node (SGSN), which communicates with the RNC. Data stream coming from the RNC are then transmitted to the BS, and finally reach the UE through the wireless interface. The proxy is able to manage data flows directly toward UEs located in different cells, which simplifies handovers. In the following subsections, we give a description of main components of the system scenario.

A. HSDPA

HSDPA allows theoretical downlink peak data rates of 14.4 Mbps, compared with 2 Mbps of UMTS. In HSDPA three new channel types have been defined: the High-Speed Downlink Shared Channel (HS-DSCH), the High-Speed Shared Control Channel (HS-SCCH), and the High-Speed Dedicated Physical Control Channel (HS-DPCCH). HS-DSCH is the transport channel used to carry users' data. Its resources can be shared among all active HSDPA users in the cell. HS-DSCH is mapped onto a pool of physical channels denominated High-Speed Physical Downlink Shared Channels (HS-PDSCHs), which are multiplexed both in time and in code. Time is handled in transmission time intervals (TTIs) of 2 ms and the code uses a constant spreading factor of 16, with a maximum of 15 for HS-PDSCHs. These channels may be all assigned to one UE during the TTI, or may be split between several users. HS-SCCH is a downlink signalling channel used to carry information between the BS and the UE before the beginning of each scheduled TTI. HS-DPCCH is an uplink low bandwidth signalling channel used to carry both ACK/NACK signalling and channel quality indicator (CQI), which provides information related to the wireless link bandwidth.

The main features introduced by HSDPA concern the use of an Adaptive Modulation and Coding (AMC) scheme, of a fast Hybrid-Automatic Repeat reQuest (HARQ) mechanism, and of a fast scheduling. The scheduler determines the terminal (or terminals) to which the HS-DSCH should transmit and, together with AMC, the data rate to be used. The scheduling algorithms are Round Robin (RR), which schedules users with a first-in first-out approach, Maximum Carrier to Interference (MAX C/I), which schedules only users that are experiencing the MAX C/I during that TTI, and Proportional Fair (PF), which provides a trade-off mechanism between RR and MAX C/I. The RR algorithm involves high fairness among all users, but it may cause a reduction of the overall system throughput since users may be served even when they are experiencing bad channel conditions. On the other hand, MAX C/I provides the maximum overall throughput for the system but it causes unfairness among users, penalizing those located at the cell edge.

B. TCP *over* HSDPA

The main characteristics of wireless networks that affect TCP's performance are the high bit error rate, the large latency, the sudden delay spikes, the consecutive time outs, and the large variations of the available link bandwidth. In particular, TCP suffers from the fast bandwidth variations of wireless channels, since the TCP adaptation to such changes is quite slow, in particular when the bandwidth increases.

Despite theHSDPA enhancements, the sender's ability of correctly estimate the round trip time and the retransmission time out remains inaccurate. Delay spikes cause sudden and short-lived increases to the round trip time. This may lead to two undesired events: spurious time outs and spurious fast retransmits. Spurious time outs are time outs that would not have occurred had the sender waited longer. The Snoop protocol provides a mechanism to counteract such time outs. Snoop maintains a cache of TCP segments sent across the wireless link not yet acknowledged by the receiver, and it locally retransmits corrupted packets without breaking end-to-end TCP semantic. Spurious fast retransmits occur when three or more packets reach the TCP receiver out of order, and when at least three of the resulting duplicate ACKs reach the TCP sender. Both spurious time out and fast retransmit are taken into account by the Eifel protocol.

III. CROSS-LAYER PROXY

In this section, we describe the RNF signalling. We consider web-browsing, or the download of files from a server on the Internet to a UE. This system is illustrated in Fig. 2. We split the connection into two TCP connections, one from the server to a proxy, and another from the proxy to the terminal. On the path from the proxy to the terminal, the most important node is the Radio Network Controller (RNC), which controls the link layer for the radio channel from the BS to the terminal.

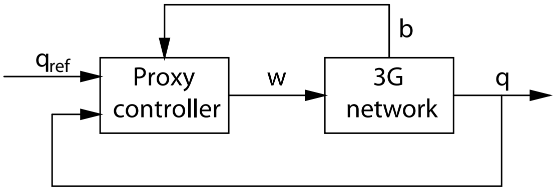

Fig. 3. Control structure. The controller uses cross-layer signalling: Event-triggered feedforward of the available radio link bandwidth b, and time-triggered feedback of the RNC queue length q. Note that both the RNC and the proxy belong to the operator's administrative domain.

To improve the TCP sender's adaptation to varying radio conditions, [13] proposes explicit cross-layer signalling (Radio Network Feedback, RNF) from the RNC, which knows the radio channel and link state, to the TCP sender. A feedback control system view is given in Fig. 3. The control signal is the window size w, and the output is the RNC queue size q, which we want to keep close to the reference value q_{ref}.

The control is based on the information in the RNF messages from the RNC, and divided in two parts. We use feedforward from the link bandwidth b, and feedback from the queue size q.

A. Feedforward of bandwidth changes

When the bandwidth of the radio link changes, the RNC generates an RNF message with the new bandwidth to the proxy. When the message is received, the proxy updates its window size according to the control law

$$w = b\hat{\tau} + q_{\text{ref}}$$

where $\hat{\tau}$ is the proxy's estimate of the round trip time, τ. With this window size, the queue size will converge to

$$q^* = q_{\text{ref}} + b(\hat{\tau} - \tau)$$

Clearly, any estimation error in $\hat{\tau}$ implies a bias in the equilibrium queue size. Measurement errors in the RNCs bandwidth also result in a bias in the queue size. To reduce the bias in the queue size, it is natural to introduce feedback of the actual queue size; this possibility is however not used in the current simulation study.

B. Generation of RNF messages

The RNC node will send RNF messages when a change on the link layer bandwidth is signaled from the BS. The question is when sending the message.

For a shared channel such as the downlink in HSDPA the bandwidth available to a UE varies continuously depending on radio conditions and cell load. Because bandwidth variations are hard to predict in the short time scale, it does not make sense to send messages each time the link bandwidth changes. Instead the RNC computes the average bandwidth for the user over a sample interval. At the end of the interval, it sends an RNF message with this average, which it is used by the proxy to predict the bandwidth during the next interval.

IV. SIMULATION STUDY

In this section, we present numerical results obtained by the implementation of TCP protocols over HSDPA through an extension of the EURANE [16] developed within the SEARCON Project [17] by Ericsson Netherlands, and other partners. EURANE is a `ns-2` simulator that includes all the new features introduced by HSDPA (such as HSDPA new channels, RR and MAX C/I schedulers, HARQ retransmission mechanism, CQI signalling, and so on). EURANE also allows us to reproduce the characteristics of the wireless channel, including the number of simultaneous users served in the cell by a BS, fast and slow fading, path loss, inter-cell and intra-cell multi-access interference.

A. Simulation Set-up

In the simulator, we have implemented the following TCP protocols:

- **Reno**. This is the base TCP scenario we have adopted. No enhancing solutions have been introduced, i.e. neither proxy nor Eifel or Snoop protocols.
- **R+S+E**. In addition to the Reno, this implementation adopts the Eifel protocol between UE and BS and Snoop protocol at the BS.
- **HTTP-PROXY**. A proxy working as a common HTTP proxy has been placed between the GGSN and the server. An HTTP proxy splits the connection between server and UE, i.e., it short cuts ACK retransmissions and packets transmissions. This proxy does not use the RNF signalling.
- **RNF-PROXY**. This is the implementation of the proxy with RNF signalling sent by the RNC, as described in section III-B.
- **RNF-PROXY+**. It is similar to RNF-PROXY, but with the addition of Eifel protocol between UE and BS and Snoop protocol at the BS.

For each one of the TCP protocol implementations, we have performed simulations for different sets of parameters: two HSDPA schedulers (MAX C/I and RR), the distance of the UE of reference from the BS (450 m and 800 m), and two propagation environments, a pedestrian (PedA) and vehicular (VehA) [17]. Pedestrian users are moving at a speed of 3 km/h and vehicular users at a speed of 120 km/h. The speed determines the coherence time of the wireless channel, and thus fluctuations of the link bandwidth. We have also varied the frequency of transmission of RNF signalling from RNC to proxy (80, 250 and 500 ms). Changing the sampling interval of the RNF means changing the sending rate of RNF signals from the RNC to the proxy, i.e. the rate at which the proxy adapts its transmission rate to the capacity of the wireless link. The minimum suitable value is 80 ms, which has been computed considering that the capacity and the delays of wired links are the following: 622 Mbit and 15 ms between BS and RNC, 622 Mbit and 0.4 ms between RNC and SGSN, 622 Mbit and 10 ms between SGSN and GGSN, 10 Mbit and 50 ms between the GGSN and the server. The radio cell accommodates 30 UEs, which are simultaneously served by the same BS. Among these users, we have picked up a reference one, and we have measured the throughput experienced for the downloading of a file during a session of 15 s. The session is long enough to account for all the variations of the link bandwidth. We set a queue size of $q_{\text{ref}} = 36$ IP packets. Furthermore, we specified a radio block error probability target of 0.1.

B. Simulation Results

In Fig. 4, the throughput experienced during the downloading session at the UE is plotted as function of time and for each of the TCP implementations, and for the pedestrian environment with the reference UE at 450 m from the BS. The available link bandwidth, which is a ceiling to the TCP throughput, is also reported. Notice that, since the downloading session is very long with respect to the fluctuations of the link bandwidth, the throughput distribution is a sufficient statistic. It can be observed that both RNF-PROXY and RNF-PROXY+ follow quite well the variations of the link bandwidth, while other implementations have deep drops. This can be explained by looking at the congestion windows in Fig. 5: while the congestion windows of the RNF-PROXY and RNF-PROXY+ exhibit a smooth behavior, those of the other implementations have large fluctuations due to the fast variations of the bandwidth. Note that the congestion windows of the RNF-PROXY and RNF-PROXY+ are taken at the proxy, while the remainder at the server. Indeed, the congestion windows of the RNF-PROXY and RNF-PROXY+ cases measured at the server are basically in congestion avoidance all the time during the file download.

The qualitative considerations done looking at previous figures can be appreciated considering Figs. 6–9, where the average throughput during the duration of the download session is reported as function of the three sampling times of the RNF. Each curve is referred to the pair TCP implementation - HSDPA scheduler. Figs. 6–7 are related the pedestrian environment, with the reference UE at 450 m and 800 m respectively. Figs. 8–9 are related the vehicular environment, with, once again, the reference UE at 450 m and 800 m, respectively. In each figure, the flat thicker line at the top is the average available link bandwidth for the UE of reference, as it is measured at the BS. Obviously, it is not dependent on the sampling times of the RNF. As a first remark, the throughput degrades as the UE is positioned far away from the BS. It is interesting to observe that in any case of the environment, position and scheduler, the throughput of the RNF-PROXY+ solution has a peak at 250ms. This can be explained as follows. The RNF rate corresponds to the window over which the past link bandwidth is averaged, and then provided to the RNF-PROXY, which controls the congestion window for the next future. The value of the average of the recent past of the link bandwidth is likely to be present also in the immediate future. Hence, an average of the recent past results in a prediction, and 250 ms seems to give the best prediction results. In the case of pedestrian environment, where the reduced mobility of the UE does not cause large fluctuations of the link bandwidth, higher RNF sampling time than 250 ms, and until 500 ms, do not reduce significantly the throughput. By the contrary, in the vehicular environment, where there are large fluctuations of the link bandwidth due to high mobility of the user, the throughput drops with higher slope as the RNF sampling time increases. Recall that high signalling rate of the RNF are expensive in term of resource utilization.

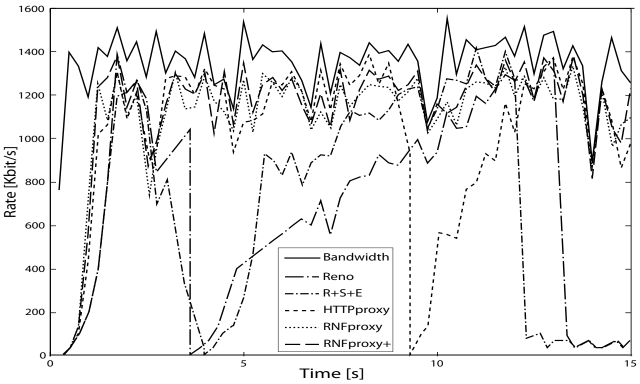

Fig. 4. Throughput for the reference UE (PedA, 450 m, 250 ms, Max C/I).

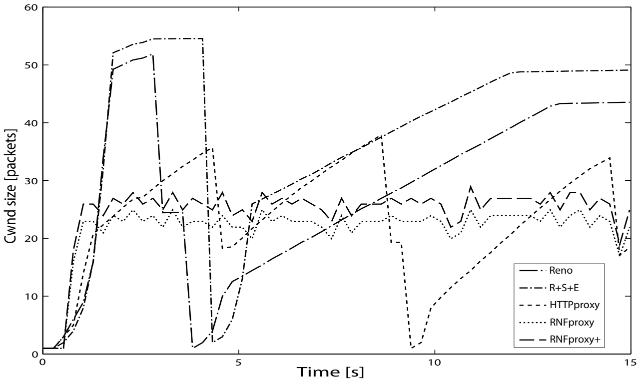

Fig. 5. Congestion window (PedA, 450 m, 250 ms, Max C/I). For the Reno and the R+S+P solutions, the cwnd is measured at the server. For HTTP-PROXY, RNF-PROXY, and RNF-PROXY+, the cwnd is measured at the proxies.

The RNF-PROXY, both in the simple version and with Eifel and Snoop, exhibits better performance in all the considered scenarios. Furthermore, adding Eifel and Snoop to either the RNF-PROXY or Reno, improves the throughput slightly. Looking at the effects of the HSDPA schedulers, the differences are also small. This is particularly interesting, since it implies that the BS can select the scheduler regardless of the TCP traffic, with potentially high advantages of other classes of services.

V. CONCLUSION

In this paper, an extensive performance characterization of a cross-layer solution for TCP over HSDPA has been presented. The solution is based on a cross-layer signalling sent from the base station to a proxy residing in the wired portion of the network. An `ns-2` simulation environment for HSDPA system has been extended and implemented. The simulator includes also the Reno, Eifel and Snoop versions of TCP, as well as the cross-layer proxy. Numerical results show that the cross-layer proxy solution significantly increases the throughput experienced by the mobile user, and thus reduces the end-

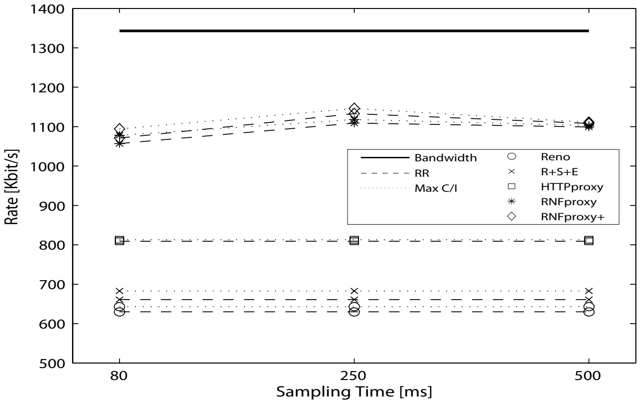

Fig. 6. Throughput for PedA environment with the reference UE located at 450 m from the BS.

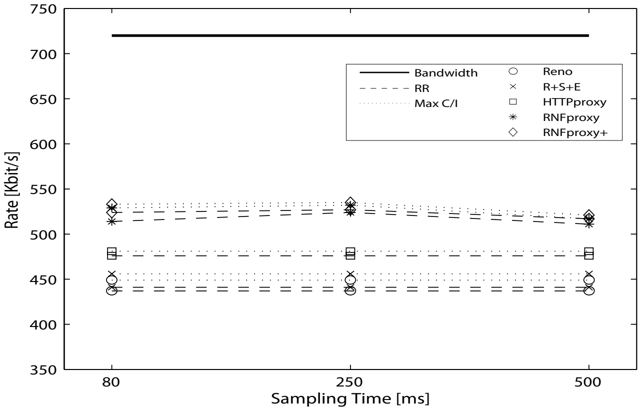

Fig. 7. Throughput for a PedA environment with reference UE located at 800 m from the BS.

to-end download time for TCP over HSDPA. Furthermore, the cross-layer proxy requires light cross layer signaling sent with low frequency, and it is not particular sensitive to the HSDPA schedulers. Thus the solution is easily implementable on existing HSDPA communication systems.

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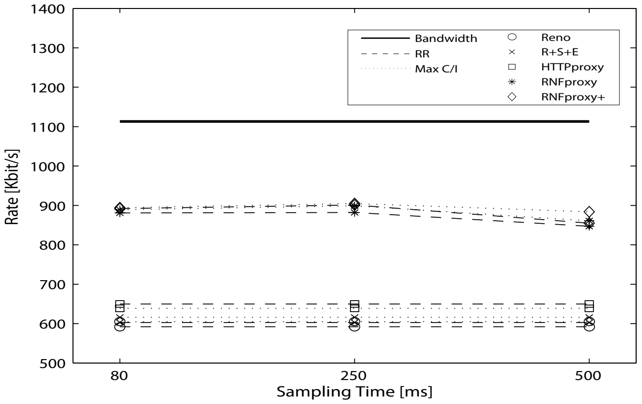

Fig. 8. Throughput for a VehA environment with reference UE located at 450 m from the BS.

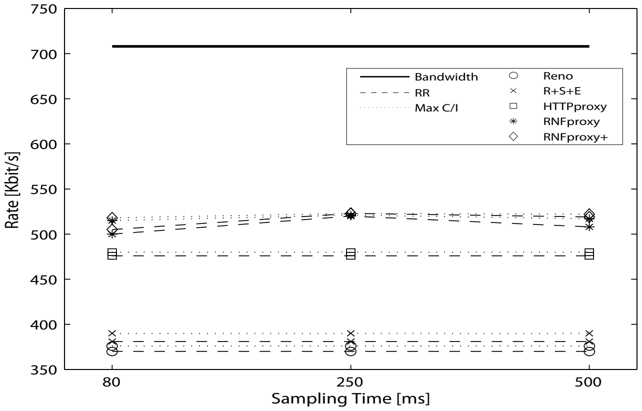

Fig. 9. Throughput for a VehA environment with reference UE located at 800 m from the BS.

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