

CAC-TCP cross-layer interaction in a HAPS-satellite integrated scenario

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Abstract—The integration of a satellite system with a HAPS segment appears very suitable to provide communication services, including Internet access, for a large set of applications. In fact, the satellite capability to provide wide coverage and broadband access can be enhanced by the use of cost-effective, mobile/portable and low-power consuming user terminals, when HAPS acts as an intermediate repeater. Moreover, also TCP-based applications, which suffer from long latency introduced by the satellite link and in general by errors, can get benefits in terms of end-to-end performance. In this frame, this paper deals with the introduction, on board the HAPS, of an efficient CAC scheme in order to guarantee an optimal utilization of the precious radio resources. In particular, we propose an innovative TCP driven CAC algorithm, which shall take into account not only the QoS requirements, but also TCP statistics obtained through a proxy installed on the HAPS. Results show that the overall system performance in terms of both average throughput and blocking probability is significantly improved.

Index Terms—CAC, Cross-Layer, HAPS, Satellite, TCP

I. INTRODUCTION

SATELLITE systems are particularly suited to support, at low cost and through a fast set up, multimedia services in sparsely populated areas or in regions where deployment of terrestrial infrastructures is impractical. In particular, these characteristics fulfill the requirements of a large set of operative scenarios where independence on terrestrial infrastructures and a rapid and cost-effective deployment of means is mandatory: exceptional events, rescue operations, emergency situations, temporary overload of the terrestrial networks, provision of Local Multipoint Distribution Services (LMDS), etc. Unfortunately, the long distance between satellite and ground segments causes drawbacks in terms of both free-space path loss and propagation delay. Such limitations affect the end-to-end performance especially in the case TCP is run as transport protocol [1]. A promising solution to both mitigate TCP problems and allow the use of small, mobile and low-power consuming terminals is based on integration of the satellite system with a quasi-stationary High Altitude Platform Station (HAPS), which can act either as stand-alone base stations or also as radio relay towards the satellite [2][3]. In particular, HAPS provides a number of

potential advantages: low propagation delay, rapid deployment time, easy maintenance, implementation of ad-hoc interfaces towards the user terminals. In this system architecture, the provision of an efficient resource management policy is one of most critical issues due to sharing of the limited radio resource among terminals presenting different characteristics in terms of mobility (fixed, portable, mobile), QoS requirements and type of service (UDP or TCP traffic). To this purpose, an adequate Call Admission Control (CAC) is needed to:

- Guarantee QoS requirements to both active and candidate users;
- Maximize the utilization of the radio resources.

In this paper, we present an innovative “TCP driven CAC” scheme taking decision on acceptance or rejection of new connections/calls not only on the basis of classical QoS physical parameters but also according to TCP statistics grabbed through a TCP proxy installed on board the HAPS. In more details, TCP statistics are used as a further input for the CAC algorithm, in order to consider also the effect of the TCP reactive congestion control mechanism in the CAC preventive decision [4]. Due to this interaction between transport layer running TCP and link layer implementing CAC driven by TCP congestion window evolution, the proposed algorithm is applicable specifically to TCP traffic, while to other traffic sources classical CAC scheme can be applied. In particular, non-TCP flows can be handled classical QoS-based CAC schemes.

To evaluate performance improvement coming from the use of the proposed TCP driven CAC scheme, with respect to a CAC scheme taking into account static parameters and physical measurements, we have developed a C++ simulator that accepts as input TCP statistics obtained by the network simulator Ns-2 [5] and allows to reproduce different communication conditions in terms of traffic intensity, percentage of TCP traffic, average Packet Error Rate (PER) and Blocking Probability Ratio (BPR).

The paper structure is the following: section II provides details on the reference scenario, section III describes the basic CAC scheme, identified to well fit the considered scenario, and the proposed extension based on a cross-layer interaction with TCP; section IV provides a description of the simulation model; section V shows simulation results, and finally section VI resumes the conclusions.

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II. REFERENCE SCENARIO

The reference scenario envisages a HAPS-satellite integrated architecture used to support the provision of a wireless Internet access to mobile, nomadic or fixed users (figure 1). In particular, we assume that a certain number of users accesses the system to download files or multimedia contents from remote servers through Internet.

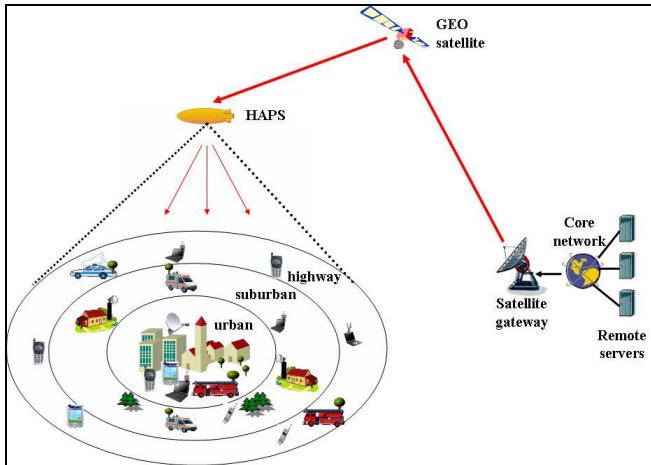


Fig. 1. Reference scenario

The HAPS operates as a network access point and data stream coming from the Internet core which is addressed to users under the HAPS footprint via a GEO satellite segment. Then, data flow follows an aggregate path of three-hops: remote server-satellite gateway, satellite gateway-HAPS, HAPS-user terminal.

User terminals can be classified according to three criteria:

1. Bandwidth requirements: three QoS classes (traffic group), with nominal data rate of 128, 256, 512 kbit/s respectively, have been identified. The reserved data rate is meant as the minimum bandwidth reservation for the whole duration of the TCP connection. Competition among different admitted TCP connections occurs when the current or the estimated congestion window requirements in terms of bandwidth exceeds the minimum bandwidth allocated per connection. To cope with this occurrence, the proposed CAC algorithm performs the probing of the TCP throughput requirements at regular intervals (Section III.B), and optionally can use “safety margins” when computing the actual rate.
2. Transport protocol: users are classified as TCP or non-TCP sources.
3. Mobility: users are classified as fixed, nomadic and mobile. In particular, fixed users are equipped with VSATs properly mounted with a line-of-sight connectivity to the HAPS. Portable terminals are easy to move (smaller size) but still work in stationary conditions. Finally, mobile users use very small terminals and can be further classified on the basis of the environment they are moving through: mobile-urban, mobile-suburban and mobile-highway. This

classification implies the use of a different channel model for each environment.

As far as the system technical parameters are concerned, the HAPS is located at an altitude of 10 km providing a single-cell coverage to a circular area of 70 km radius. Only 10 Mbit/s are dedicated to the provision of services by the integrated HAPS-satellite system, while the rest of the available bandwidth, both on the HAPS and satellite, is utilized to satisfy other telecommunication needs (study case not referred to any real system).

Finally, downlink channel is accessed through a FD-TDMA (Frequency Division TDMA) technique that, according to the proposed CAC scheme, dynamically assigns time slots/channel on the basis of the instantaneous needs of each active data transfer.

III. A TCP DRIVEN CAC SCHEME

A. “Basic” CAC scheme

To evaluate the improvement introduced by a CAC-TCP interaction the performance of a “basic” CAC algorithm, which fulfills the requirements of the considered scenario, will be considered as a benchmark.

The presence of three QoS classes with different nominal data rate requires a CAC algorithm able to take its decisions according to a priority-based policy. In fact, if all the users have the same access priority regardless their traffic class, the low data rate (128 kbit/s) users shall have higher probability of being admitted, while high data rate (512 kbit/s) users shall be practically excluded from the network as the load increases.

To this purpose, we have considered the weighted priority scheme proposed in [6] which is based on the definition of the blocking probability ratio (BPR) of each pair of supported QoS classes. Consequentially, the aggregate bandwidth is divided into a number of segments equal to the number of supported QoS classes. In fact, without such a differentiation, the higher is the class QoS requirements, the lower the probability that a new TCP connection is accepted. Therefore, a new connection is admitted only if the bandwidth assigned to its QoS class is sufficient, and fairness in terms of bandwidth allocation will be guaranteed by choosing the most appropriate BPR values.

B. CAC-TCP interaction

The considered scenario is characterized by a high delay due to the GEO satellite segment (the round trip delay is about 560 milliseconds) and transmission errors on both satellite and HAPS segment depending on propagation conditions. Such conditions affect TCP performance as largely reported in the literature [1][7][8][9]. In fact, packet losses reduce TCP transmission window, while TCP reaction time to recovery the optimal window is slowed down by the long perceived delay [10]. In this context, by considering a dynamic resource allocation scheme taking into account TCP dynamics in order to optimize utilization [11], a CAC scheme considering also the constraints risen at the transport level is recommended.

In fact, the “basic” CAC scheme, based only on static

parameters, can lead to two nested events:

- Accepted TCP connections don't use the whole assigned capacity;
- New connections are refused even though some capacity is unused.

To avoid this capacity waste, we propose a cross-layer interaction between transport layer and link layer aiming to inform CAC about the real needs of TCP. In practice, a TCP proxy installed on board the HAPS monitors all the active connections in order to continuously grab information about TCP transfer rate and assign capacity accordingly. Then, samples of the current data rate are computed for each connection at regular intervals and passed as input to the CAC algorithm which uses such information to estimate the unused capacity and monitor the maximum achievable rate for each QoS class. The latter parameter will replace the nominal rate in the CAC decision to accept or reject a new connection. Of course, in case TCP throughput is not limited by any constraint (i.e. low PER), CAC scheme simply uses the nominal rate as parameter for the decisions.

IV. SIMULATION MODEL

Both the TCP driven and the basic CAC scheme have been simulated through the offline combination of two simulation tools that run sequentially. First, the Network Simulator ns-2 [5] is used to configure the communication nodes, the link parameters and the communication protocols. At the application layer FTP protocol runs over a TCP Reno connection (packet size 1460 bytes). As output, ns-2 simulations provide TCP statistics of the user terminals characterized by the channel model of the mobility-group which they belong to and the nominal rate of their QoS class. Additionally, an ad-hoc C++ simulation tool has been developed to reproduce the overall network environment and manipulate TCP measurements. In most details, the C++ tool gets as inputs the TCP statistic files generated by the ns-2 simulations and provides the following functionalities:

- it runs either the basic QoS-based or the TCP driven CAC algorithm;
- it calculates the instantaneous and average throughput of the network;
- it computes the connection blocking probability of each QoS class as well as the aggregate connection blocking probability of the network.

To reproduce reliable TCP statistics, packet error distributions (derived at TCP level), suitable for HAPS communication, have been considered in the ns-2 simulations. First, we considered the Satellite-HAPS link as error free. This assumption appears rather realistic since in such a link only the free space attenuation incurs and errors due to the atmosphere layers can be for example counterbalanced by improving the satellite gateway EIRP. Therefore, the adopted channel models are referred uniquely to the HAP-user terminal link. In particular, two approaches have been followed, depending on the mobility characteristics of the user terminal:

1. In the case of either fixed or portable terminals, we assume line-of-sight (LOS) conditions always ensured. Thus, time-uniform packet loss distributions (TCP level), indicating no correlation among subsequent losses, are used with mean values equal to 10^{-4} (for fixed) and 10^{-3} (for portable).
2. In case of mobile terminals for each environment (urban, suburban and highway) we consider a two-state channel model [12] to characterize the alternating LOS and shadowing conditions. The "bad" state has an average duration consistent with values provided in [12] and leads to the dropping of all the TCP packets in flight (PER=1). Instead, during the "good" state, an uniform packet loss distribution with a low average PER is considered.

V. PERFORMANCE EVALUATION

The C++ event driven simulator manages both arrival and termination of TCP connections as Poisson processes [6]. Thus, the time between two successive arrivals of users (τ) and the duration of each admitted connection (d) follow exponential distribution with mean value $1/\lambda$ and $1/\mu$ respectively:

$$\begin{aligned} \text{pdf}(\tau) &= \lambda \cdot e^{-\lambda\tau}, E[\tau] = \frac{1}{\lambda} \\ \text{pdf}(d) &= \mu \cdot e^{-\mu d}, E[d] = \frac{1}{\mu} \end{aligned} \quad (1)$$

The parameters $E[d]$ and $E[\tau]$ along with the aggregate number of users in the network (S) determine the traffic load of the network (L).

Using as performance metrics the blocking probability and the average throughput, we have analyzed the improvement achieved by the proposed TCP driven CAC scheme (with respect to the "basic" CAC scheme) under different network conditions in terms of: traffic intensity (L), average PER, and percentage of TCP users (TCP_perc). In general, throughput improves because the available bandwidth is optimally utilized taking into account variability of capacity requirement for each link due to the dynamic evolution of the congestion window for TCP based traffic.

A. Traffic intensity

Figure 2 shows the improvement (%) coming from the adoption of the TCP driven CAC scheme, in terms of blocking probability decrease and average throughput increase, for a wide range of traffic load (L). Moreover, an uniform distribution of the users among the mobility groups as well as equal blocking probability of the three QoS classes ($BPR=1$) is considered. Finally, all users are assumed running TCP applications. Results highlight as the improvement is overall considerable and grows for higher traffic load values: 45% reduction of the blocking probability and about 16% increment of the average network throughput. As an absolute reference, performance when the basic CAC is operating can be summarized as follows:

- The overall bandwidth utilization ranges from 57% ($L=9000$) to 67,5% ($L=12250$).

- The blocking probability ranges from 17% (L=9000) to 60% (L=12250).

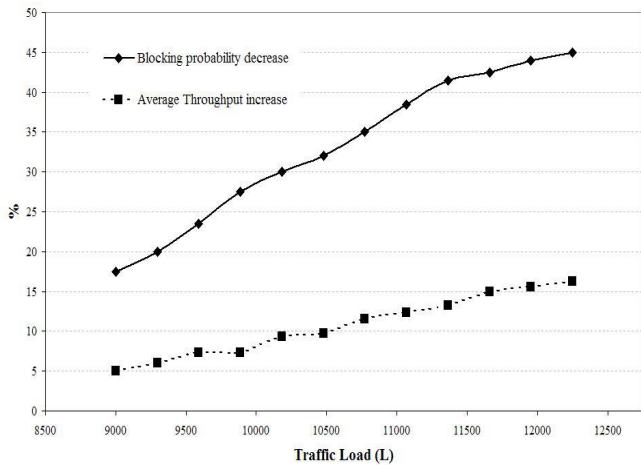


Fig. 2. Blocking Probability decrease and Average Throughput growth vs. Traffic Load (kbit/s)

B. Average PER

Since the mobility groups are characterized by different channel models, we consider the average PER of each mobility group ($E[PER(\textit{“mobility_group”})]$) as an identification parameter of the channel quality. For sake of simplicity, an unambiguous average PER value (av_PER) related to the network can be expressed as follows:

$$av_PER = \sum_{k \in M} perc(k) \cdot E[PER(k)] \quad (2)$$

where:

- $M=5$ is the number of mobility groups;
- $perc(k)$ denotes the percentage of the k^{th} group in the total number of served terminals.

By considering a traffic load of 10800 kbit/s, BPR=1 and TCP_perc=100, figure 3 shows as increasing the network average PER (higher percentage of mobile terminals) the blocking probability decreases accordingly, while the average throughput growth is quite flat (about the 10%). In absolute terms, TCP driven CAC allows to achieve capacity utilization up to 85% (average_PER = 0.0041) and a blocking probability approaching zero while average_PER is increasing.

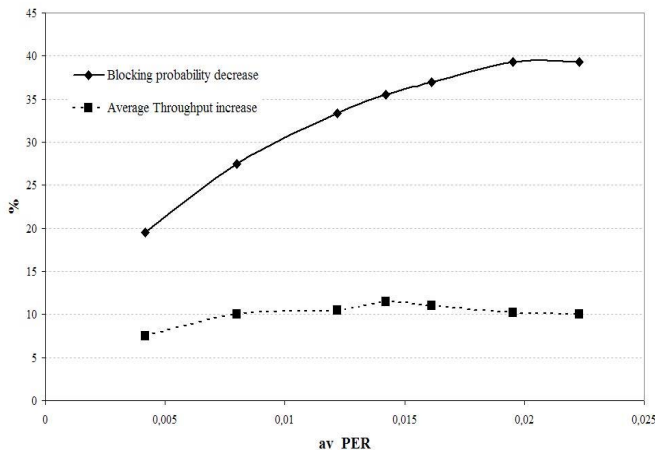


Fig. 3. Blocking Probability decrease and Average Throughput growth vs. average PER (for the different terminal classes)

C. Percentage of TCP users

Since the proposed TCP driven CAC scheme is applied only for TCP flows, the virtue of such a scheme is rather dependent on the percentage of TCP users. In this respect, figure 4 presents the blocking probability decrease and the average throughput increase for a variety of TCP_perc values (BPR=1, uniform distribution of the users among the mobility groups, L=10800 kbit/s).

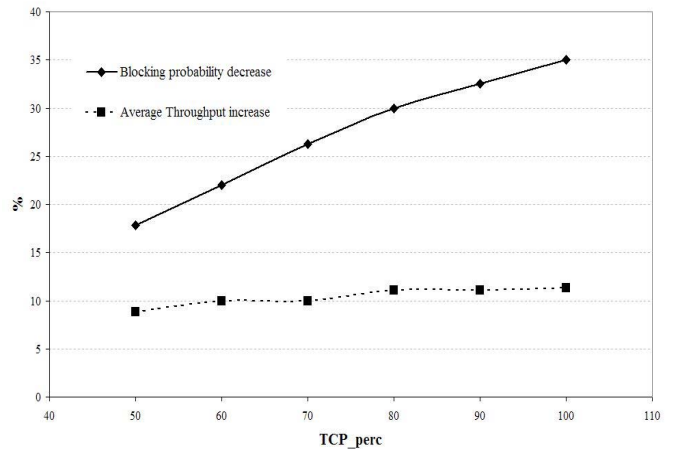


Fig. 4. Blocking Probability decrease and Average Throughput growth vs. percentage of TCP connections

VI. CONCLUSION

An integrated Satellite-HAPS architecture represents an innovative and challenging solution to guarantee broadband telecommunication services in a large set of scenarios where the deployment of terrestrial infrastructure is not cost-effective or indeed impossible. Furthermore, the introduction of the HAPS segment allows to serve also mobile users equipped with very small terminals with respect the typical VSATs.

In this frame, the implementation of an appropriate CAC algorithm can greatly help in ensuring QoS for multimedia services. On the other hand, applications running TCP as transport, present sub-optimal performance due the physical characteristics regardless the pre-assigned bandwidth.

In this paper, we proposed a new TCP driven CAC algorithm aiming to ensure both QoS for multimedia services and optimal resource utilization when also TCP flows share the overall capacity.

Through simulation, we demonstrated a considerable improvement of the performance with respect to a basic CAC algorithm that takes into account only QoS requirements and physical parameters.

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