Network Architectures to Improve the Performance of the Transport Layer in Satellite Communications

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Abstract
The paper began proposing two possible frameworks where the different solutions to improve the performance of the transport layer over satellite channels may be classified: the Black Box (BB) approach and the Complete Knowledge (CK) approach. The former implies that only the end terminals may be modified; the rest of the network is considered non-accessible (i.e. a black box). The latter allows tuning parameters and algorithm of the network components. Most of the previous research has been based on the Black Box approach.

The advantages that derive from both the approaches are utilised to design a novel network architecture suited for satellite transportation, where the transport layer is divided into two parts, one of them completely dedicated to the satellite portion of the network (Satellite Transport Layer - STL). The two components of the transport layer are joined by Relay Entities, which imply a complete redefinition of the protocol stack on the satellite side (Satellite Protocol Stack - SPS).

The new Satellite Transport Layer, based on the CK philosophy, will use a specific Satellite Transport Protocol (STP), obtained by a parameterisation, based on the TCP (Transmission Control Protocol), to meet all the network requirements and characteristics in terms of delay, reliability and speed.

The Satellite Protocol Stack will operate also at the network layer and will benefit from possible resource allocation features of the layer 2 (data link) and, in particular, of the MAC (Medium Access Control) sub-layer.

The paper presents some results, aimed at showing the performance that the new architecture can provide. The results have been obtained in a real satellite test-bed by using a simplified architecture, aimed at emulating the SPS.

I. INTRODUCTION
The TCP/IP protocol stack is currently widely applied. Most of the applications used to transmit audio, video and data utilise the mentioned stack. In the same time, satellite networks have increased their importance. They provide outstanding advantages with respect to terrestrial networks and they are often used both as access and as backbone networks. So, the development of tools to allow the efficient utilisation of TCP/IP - based applications over satellite networks and heterogeneous networks, which involve satellite portions, is an important and hot topic [1].

In more detail, a problem deserving a special attention is the reliable transmission of data. WEB navigation, file transfer and data base access are examples of applications that require a reliable exchange of data. The tool used to guarantee a reliable stream delivery is the Transmission Control Protocol (TCP) [2], which uses an acknowledgement mechanism to assure a safe delivery. The acknowledgement strategy is made very inefficient by the long Round Trip Time - RTT (defined as the overall time required to send a unit of information and to get back the acknowledgement from the destination) of a satellite network. In a geostationary - GEO satellite environment (where the results presented in the paper have been obtained), the RTT is above 500 ms. As a consequence, the throughput of the transmissions is so low to heavily affect the quality of service perceived by the users of the mentioned applications, based on the TCP/IP protocol stack. The performance of the overall transmission may be strongly improved by a re-design of the transport layer. Projects about this topic are common within the framework of the satellite networking research.

Also International Standardisation Groups as the Consultative Committee for Space Data Systems - CCSDS [12], which has already emitted a recommendation (reference [13]) and the European Telecommunications Standards Institute - ETSI [14], which is beginning its activity within the framework of the SES BSM group [15], are active on these issues.

The paper presents a possible classification of the various approaches, at first. The proposal concerns the Black Box (BB) and the Complete Knowledge (CK) approach. The former allows modifying only the protocol stack at the source and at the destination because the network between the end terminals, including network devices as routers, is considered as a black box. The latter supposes the complete control of any network devices and allows a joint configuration of all the functional layers involved to get an optimised network resource management aimed at improving the overall performance offered by the network. The paper, then, proposes a protocol architecture, designed for a heterogeneous network involving satellite portions, which conveys the benefits both from the Black Box and the Complete Knowledge approach. The satellite portion of the network is isolated by using Relay Entities, which use a modified protocol stack on the satellite side (the Satellite Protocol Stack - SPS), whose transport part is called STL (Satellite Transport Layer). The STL protocol (called Satellite Transport Protocol -STP) is parameterised by using an approach already proposed in the literature for end terminals within the BB approach.

The SPS network layer and, as a consequence, the transport layer, may utilise the features of a proper data link layer (layer 2), offering the upper layers a service about the availability of the network resources. A resource allocation mechanism, even if not strictly necessary, may improve significantly the performance of the proposed architecture.

The paper is structured as follows. Section II contains the description of the two proposed approaches: Black Box and Complete Knowledge. Section III shows the Satellite Protocol Stack architecture proposed and some ideas about the design of the Relay Entity. The parameterisation of the Satellite Transport Layer is summarised in section IV. The results are reported in section V. Section VI contains the conclusions.

II. THE 'BLACK BOX' AND THE 'COMPLETE KNOWLEDGE' APPROACHES.

The network configuration used in the tests reported in the paper is reported in Fig. 1. The box identified as APPLICATION PC may also represent a local area network (LAN). The system employs the satellite ITALSAT II. It provides coverage in the single spot-beam on Ka band (20-30 GHz). The overall bandwidth is 36 MHz. Each satellite station can be assigned a full-duplex channel with a bit-rate ranging from 32 kbits/s to 2 Mbits/s, this latter used in the experiments, and it is made up of the following components:

- Satellite Modem, connected to the RF device.
- RF (Radio Frequency) Device.
- IP Router connected to:
  - Satellite modem via RS449 Serial Interface
  - Application PC via Ethernet IEEE 802.3 10BASE-T link
- Application PC: PCs Pentium III 500 MHz. They are the source of the user service.

![Fig. 1. Test-bed Network.](image-url)
end user terminals. The rest of the network is considered as a black box, where, even if the intermediate devices and the configurations are known, they cannot be modified.

Many results have been obtained with this model. The best configurations (taking file transfer as reference application and the overall transmission time and the instantaneous throughput as metrics) have been used for WEB navigation over the satellite network [17, 18].

An alternative approach is supposing the complete knowledge of each network device (e.g. routers, modems, and channel characteristics) and the possibility to modify the configurations to improve the performance of the overall satellite network (or of the satellite portion of the network). The approach is possible if the network is small and proprietary. In this case an example of action to take is the intervention on the IP router because the buffer management and dimension is very important to improve the network performance.

III. SATELLITE PROTOCOL STACK (SPS) ARCHITECTURE

The general architecture is reported in Fig. 3. The network is composed of terrestrial portions, represented by the Internet in the figure, and of a satellite portion (a backbone, in this case). The latter is isolated from the rest of the network by using Relay Entities. Only two of them are shown in the figure but, actually, one Relay Entity is required whenever a satellite link is accessed.

The architecture is based on the work published in the literature about TCP splitting and spoofing [1, 3, 4, and 8] but, in this case, the protocol stack on the satellite side is completely re-designed. The transport layer of this new Satellite Protocol Stack (SPS) is called Satellite Transport Layer (STL) and it implements a Satellite Transport Protocol (STP), suited for the specific environment.

From the protocol layering point of view, the key point is represented by the two Relay Entities, which are two gateways towards the satellite portion of the network. The SPS acts on the satellite links by using the necessary information because it has the knowledge and the control of all the parameters. The Relay Layer guarantees the communication between the satellite transport layer and the protocol used in the cable part (i.e. TCP).

Two possible alternatives may be chosen concerning the transport protocol:
- bypassing completely the concept of end-to-end service at the transport layer;
- preserving the end-to-end characteristic of the transport layer.

The first choice is represented in Fig. 4. The connection at the transport layer is divided into two parts, dedicated, respectively, to the cable and the satellite part. The source receives the acknowledgement from the first Relay Entity, which opens other connections, with different parameters based on the current status of the satellite portion, and allocates the resources available. The Relay Entity on the other side of the satellite link operates similarly towards the destination. The transport layer of the cable portions is untouched. The end-to-end connection may be guaranteed only statistically.

The second choice is aimed at preserving the end-to-end characteristic of the transport layer. In this case also the transport protocol in the terrestrial portion should be modified. A possibility may be dividing the transport layer into two sub-layers: the
upper one, which guarantees the end-to-end characteristic, and the lower sub-layer, which is divided into two parts (as the overall transport layer in the first choice) and interfaces the STL. The terrestrial side of the lower transport layer may be also represented by the TCP. Fig. 5 shows the protocol architecture in this case. The transport layer is modified even if the interface with the adjacent layers may be the same as in the TCP.

Both the choices are currently under investigation; the preservation of the end-to-end characteristic is one of the object of the new Project, "Transport Protocols and Resource Management for Mobile Satellite Networks" funded by the European Space Agency (ESA) and carried out by CNIT. This project is aimed at designing, implementing and testing a protocol stack adapted to the specific characteristics of a satellite communications system. The protocol stack will be based on the TCP/IP suite adapted to the channel characteristics. The objective is the optimisation of both the transport protocol performance for a mobile and fixed satellite network environment and the efficient utilisation of network resources. This will be achieved without re-designing the protocol interfaces, so that they will keep the same characteristics of the interfaces currently used. These characteristics should get the target of maximising the system performance and, in the same time, allow the utilisation of standard applications so reaching a high degree of portability.

The proposed protocol architecture is targeted to mobile and fixed satellite communication systems. The environment has a wide range: it includes the characteristics and the related problems of radio-mobile and LEO (Low Earth Orbit) satellite systems, as fading and high bit-error rate, and of GEO (Geostationary Orbit) satellite environments, where the high round-trip delay will heavily affect the system performance. The protocol stack has a high degree of flexibility to allow an efficient adaptation to these characteristics. Some ideas about the characteristics of the transport protocol will be presented in the next section. Details about the architecture of the Relay Entity are reported in the following.

The performance of the Relay Entity strictly depends on the design of each layer. An idea is reported in Fig. 6, where the architecture of a Relay Entity is shown. The protocol stack is completely re-designed on the satellite side. The essential information concerning each layer (Transport, Network and Data Link) of the terrestrial side may be compressed in the Relay Layer PDU (Protocol Data Unit), i.e. a specific unit of information created in the Relay Layer. The Data Link layer (the Medium Access Control sub-layer, in this case) offers to the upper layer a Bandwidth Reservation service, a sort of Bandwidth Pipe available to the Network Layer, which can itself reserves resources for the Transport Layer. The Network Layer may use the structure of the IP layer but it may be properly designed together with the STL layer, so to avoid the possibility of the event 'congestion' (and, for instance, the consequent 'congestion avoidance' phase, if a standard TCP was used) and to optimise the performance of the overall transmission on the satellite side. The Network Layer may reserve resources by using the Integrated
Services [19] or the Differentiated Services [20] approach, considering the two possibilities offered in the IP world. Anyway, the aim is to create a bandwidth pipe (Relay Entity - to - Relay Entity, in the satellite portion), so to offer a dedicated channel to a single connection at the transport layer or to a group of connections at the transport layer. If it is not possible, the pipe shown in Fig. 6 may be simply represented by the transfer capacity of the physical interface. In this latter case, all the connections of the STL share the same portion of bandwidth and the STL design must take it into account.

<table>
<thead>
<tr>
<th>RELAY LAYER</th>
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<tbody>
<tr>
<td>Lower Transport Layer</td>
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<tr>
<td>IP</td>
</tr>
<tr>
<td>Data Link - MAC</td>
</tr>
<tr>
<td>PHYSICAL</td>
</tr>
</tbody>
</table>

Fig. 6. Design of the Relay Entity.

The architecture proposed may be a valid alternative both in case the satellite portion represents a backbone network and both in case it represents an access network. Fig. 3 contains the already presented proposal in the backbone case. Fig. 7 shows the possible solution in the access case: the Relay Entity is a simple tool, directly attached to the Application PC. It may be also a hardware card inside the Application PC.

Table 1 contains some of the TCP characteristics. The parameters and the notation are substantially set following the standard in [21] and [22]. A C-like language is used for the description. The acronym cwnd stands for the congestion window, smss is the sender maximum segment size, and ssthresh is the slow start threshold. FlightSize is the measure (in bytes) of the amount of data sent but not yet acknowledged, i.e., the segments still in flight. The real transmission window (TW) is set, in any case, to the minimum between cwnd and the minimum between the TCP buffer dimension at the source and the receiver's advertised window (rwnd), which is the half of the receiver TCP buffer length. The receiver window rwnd has been measured to be 32 Kbytes at the beginning of the transmission. The receiver buffer space is automatically set by the TCP to 64 Kbytes.

IV. **Satellite Transport Protocol (STP)**

Fig. 7. Access Network.
Table 1. TCP parameters.

| TW=min\{cwnd, min(source buff, rwnd)\} | cwnd=1·smss |
| SLOW START [cwnd<ssthr] | ssthre=\infty\ | ACK \rightarrow cwnd=cwnd+1·smss |
| CONGESTION AVOIDANCE [cwnd>ssthr] | <cwnd> ACK \rightarrow cwnd=cwnd+1 |
| FAST RETRANSMIT / RECOVERY | ssthre=max\{FlightSize/2, 2·smss\} |
| | cwnd=ssthre+3·smss |
| | Delayed ACK \rightarrow cwnd=cwnd+1·smss |
| | cwnd=ssthre |

Table 2. STP.

| TW=min\{cwnd, min(source buff, rwnd)\} | cwnd=IW·smss |
| SLOW START [cwnd<ssthr] | ssthre=Th |
| | ACK \rightarrow cwnd=cwnd+F(\text{# of received acks, cwnd})·smss |
| CONGESTION AVOIDANCE [cwnd>ssthr] | <cwnd> ACK \rightarrow cwnd=cwnd+G(cwnd, \bullet) |
| FAST RETRANSMIT / RECOVERY | ssthre=max\{FlightSize/2, 2·smss\} |
| | cwnd=ssthre+3·smss |
| | Delayed ACK \rightarrow cwnd=cwnd+1·smss |
| | cwnd=ssthre |

Table 2 contains a proposal for the STP, i.e. the protocol implementation for the Satellite Transport Layer (STL). The parameters \(IW\) and \(Th\), along with the two functions \(F(\cdot)\) and \(G(\cdot)\) may be tuned following both the characteristics of the physical channel (delay, loss, bit error rate,…) and the network status (e.g. congestion). The function \(F(\cdot)\) is aimed at regulating the size of the congestion window in the SLOW START phase. The characteristics of \(F(\cdot)\) affect the increase of the window and, as a consequence, the transmission speed and the protocol performance. The definition of \(F(\cdot)\) is not trivial and many considerations may affect the decision. Possible proposals concerning the function \(F(\cdot)\) for GEO links may be found in reference [16]. The increment in cwnd strictly depends on the current value of the cwnd itself and on number of received acknowledgements, as indicated in Table 2. The choice allows to tune the behaviour of the protocol in dependence of the congestion window, and to measure, at some extent, the network status represented by the arriving acknowledgements. The function \(G(\cdot)\) is aimed at regulating the behaviour of the CONGESTION AVOIDANCE algorithm. The modification of the congestion avoidance scheme has not provided outstanding results over GEO channels but it might be very useful in LEO or radio-mobile environments.

V. RESULTS

A preliminary implementation of the SPS is analysed. The test-bed used is sketched in Fig. 1. Actually, the SPS architecture is not completely implemented. The Relay Entity in Fig. 6 is emulated by implementing, in the Application PCs, the STP proposed in section IV and a proper buffer tuning at the network layers of the intermediate routers. The solution refers to the Complete Knowledge approach.

The configuration under analysis (identified as STL, in the following) is compared with a TCP configuration, adapted to the satellite GEO environment, identified as Modified TCP (Reference). This solution, which refers to the Black Box approach, is implemented only in the Application PCs. It applies an \(IW=2\) and a TCP buffer of 320 Kbytes both at the source and at the destination. This choice is due to the fact that this configuration resulted as one of the most efficient and less dangerous, concerning the congestion risk. It guaranteed a gain over 70% with respect to the TCP commonly used, in the Black Box case [10].

The comparison is aimed at showing the further improvement of the STL with respect to a modified TCP configuration, already adapted to satellite channels in previous studies. The results should give an idea of the possible advantages deriving from the SPS architecture.

Table 3 shows the gain of STL with respect to the Modified TCP for a file transfer of 3 Mbytes. The gain is computed in percentage (e.g. the value 21.9% in Table 3 is obtained as \(100 \times (16.05-12.54)/16.05\)).

The same quantities for a file transfer of 100 Kbytes are contained in Table 4. The improvement is very relevant for short file transfers. The effect in a remote control system (e.g. tele-robot, tele-control) may be simply guessed.

The behaviour when more than one connection shares the bandwidth is reported in Fig. 8, for a 100 Kbytes file transfer. Gain is kept up to a relevant number of connections. The Modified TCP Reference configuration, although very convenient with respect to the TCP commonly used, not shown here, may be strongly improved.
The last part of the results investigates the behaviour of the new transport protocol when there are packet losses due to channel errors. The losses have been artificially introduced. The modem has been shut down for a fraction of second. The IP router has been properly configured to avoid losses due to congestion.

Table 5 contains the gain for a 3 Mbytes transfer in the mono-connection case. Actually, the packet loss is more intense for STL, due to a more aggressive behaviour in the first phase of the connection, where the shut down happens. It recovers thanks to the correct interpretation of the losses, which are not due to congestion, as wrongly estimated by the Reference configuration.

<table>
<thead>
<tr>
<th>Transport Protocol</th>
<th>Overall Transmission Time [s]</th>
<th>Gain</th>
</tr>
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<tbody>
<tr>
<td>Modified TCP (Reference)</td>
<td>16.05</td>
<td>-</td>
</tr>
<tr>
<td>STL</td>
<td>12.54</td>
<td>21.9 %</td>
</tr>
</tbody>
</table>

Table 3. Overall Transmission Time and Gain, 3 Mbytes file transfer, mono-connection.

<table>
<thead>
<tr>
<th>Transport Protocol</th>
<th>Overall Transmission Time [s]</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified TCP (Reference)</td>
<td>3.7</td>
<td>-</td>
</tr>
<tr>
<td>STL</td>
<td>0.6</td>
<td>83.8 %</td>
</tr>
</tbody>
</table>

Table 4. Overall Transmission Time and Gain, 100 Kbytes file transfer, mono-connection.

![Fig. 8. Throughput versus number of connections, 100 Kbytes file transfer, multi-connection.](image)

VI. CONCLUSIONS

A new Satellite Protocol Stack architecture has been proposed in the paper. The reference network includes satellite portions, which have been isolated from the rest of the network by using Relay Entities. The Relay Entities contain a protocol stack properly designed to improve the performance on the satellite portion. A Transport Layer, called STL - Satellite Transport Layer, a Network Layer and a Data Link Layer, composes it. STL implements the Satellite Transport Protocol (STP), which adapts its parameters and algorithms depending on the performance offered by the lower layers. For example, Network and the Data Link layers may implement bandwidth reservation schemes, which, together with the STP, may improve the performance of the overall system. The overall architecture proposed works both if the satellite portion represents a backbone network and if it is an access network.

The results, obtained by measures in a real satellite test-bed, which represents a simplified version of the new architecture proposed, show an outstanding performance improvement with respect to a modified version of the transport layer, which had provided already excellent results in previous studies. The improvement is more evident for short file transfers and in presence of transmission errors. The effect is due to the radical modification of the protocol structure. On one hand, the previous approach was based on the structure of the TCP, which was tuned and adapted to the characteristics of the satellite links. On the other hand,
the approach presented proposes a new Satellite Protocol Stack (SPS), whose action is not limited to the transport layer but it includes the network and data link layer. Even if the results have been obtained by using a simple test-bed that does not consider all the possible features of the new architecture, it allows having an idea of the SPS performance.

ACKNOWLEDGEMENTS

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REFERENCES


