

# Protocol Stack options in heterogeneous aeronautical networks

Christian Kissling, German Aerospace Center, Cedric Baudoin, Thales Alenia Space

**Abstract**—In the future the amount of air traffic as well as the total data traffic volume of aeronautical communication will significantly increase. A single terrestrial technology alone will likely not be able to manage this challenge but satellite communication systems will serve as complement to direct air to ground data links. The future Air Traffic management (ATM) will thus consist of highly heterogeneous networks consisting of diverse technologies. It is highly important to design the network protocol stack in a way that allows interoperability of all involved networks while being transparent to the end users and providing the required levels of QoS performance, especially in the presence of transport layer protocols like TCP. This paper presents three different protocol stack alternatives dealing with the mentioned issues, investigates their advantages and disadvantages and proposes a protocol stack fitting the needs of ATM communications.

## I. INTRODUCTION

**D**UE to the high increase in number of worldwide flights and their increased communication volumes (also caused by introduction of new services and migration from voice to data) future ATM will require a change in the communication paradigm to be able to cope with this challenge. Already today, the capacity of existing ATM systems is close to saturation and it is expected that the existing systems will not be able to provide the necessary capacity in 10-15 years (according to Eurocontrol), even if modifications and changes to the existing systems will be applied. For this reason it is very likely that existing terrestrial communication systems will be complemented by other technologies such as different satellite communication technologies (LEO, MEO or GEO), ad-hoc networks among aircraft and new terrestrial communication links such as Broadband Aeronautical Multi-Carrier communications (B-AMC). Whether the technologies will be 100% complementary or just contribute to an overall system is currently under discussion and definition. But it is clear that all these technologies have very heterogeneous characteristics such as different delay, available bandwidth and packet error rates. Within the NEWSKY project it is investigated how all these diverse links can be integrated

This work has been partially conducted in the framework of the NEWSKY Project, co-funded by the European Commission. This paper, however, does not implicitly represent the opinion of all project partners and the European Commission. The authors are solely responsible for it. The European Commission is not responsible for the use of any data in the paper

Christian. Kissling is with the German Aerospace Center (DLR), Oberpfaffenhofen, D-82234 Wessling, Germany, phone: +49-8153-28-2891; fax: +49-8153-28-2844; e-mail: [christian.kissling@dlr.de](mailto:christian.kissling@dlr.de).

Cedric Baudoin is with Thales Alenia Space France, Toulouse, e-mail: [cedric.baudoin@thalesaleniaspace.com](mailto:cedric.baudoin@thalesaleniaspace.com)

into one global heterogeneous aeronautical communication network and which mechanisms and architectures are required to ensure that the strict requirements of aeronautical communication are met. Moreover NEWSKY is not only looking into existing link technologies but is open to integrate also links which will emerge in the future and are not yet defined.

When integrating these diverse links into one global network many challenges arise. This paper investigates which alternatives for the protocol stack in such an environment exist to support common signalling (vertical and horizontal QoS signalling and cross layer signalling independent of the underlying link technology which is used) and in a way that the communication efficiency is optimized.

In the legacy Aeronautical Telecommunication Network based on OSI protocols (ATN/OSI) two transport layer protocols have been specified for use in ATN end systems [1]: The *Connection Oriented Transport Protocol* (COTP) and the *Connectionless Transport Protocol* (CLTP).

For the COTP an end-to-end connection mode service is offered to the users, which provides a reliable connection over unreliable lower layers in addition to flow and error control. To accomplish this, the COTP protocol splits the data streams of the different applications into several segments and adds an additional header to each segment before handing the data over to the network layer. During reception, the COTP protocol orders the received datagrams and reconstructs the original data stream. In case some datagrams have been lost, the protocol initiates a retransmission of them. This way integrity and sequence integrity are provided.

For the CLTP only an unreliable, connectionless service is provided. This means that no guarantee is given that a sent datagram really arrives at the receiver. Moreover no guarantee of the order of reception of datagrams is given here.

In an IP environment, such as envisaged by NEWSKY for the future ATN (ATN/IPS), the most popular transport layer protocols are the Transmission Control Protocol (TCP) and the User Datagram Protocol (UDP). While UDP corresponds to a connectionless transmission service as CLTP not providing any guarantees about the correct reception at the receiver or the order of reception, the TCP protocol guarantees reliable and in-order delivery of the datagrams to the application layer. At the moment the role of the transport layer protocols in the ATN is still to be defined. However it can be expected that both TCP and UDP will play an important role in the provision of ATM [8]. While commonly deployed versions of the TCP protocol (such as TCP Reno or TCP New Reno) perform quite well in fixed terrestrial networks with low delay and very low packet error

rates (PER), their performance degrades significantly in presence of wireless links. This is mainly because the assumption of small delay is no longer valid. The future ATN/IPS as envisaged in NEWSKY should be open to include links of different technologies such as VHF radio links as well as satellite communication links using GEO satellites. Especially for the usage of GEO satellites the perceived link properties differ significantly from the ones of terrestrial networks. Satellite links have in general the following properties:

- Long and very long delays
- Large delay · bandwidth product
- Higher packet losses and fading channels
- High asymmetry of data rates in uplink and downlink (or forward link and return link in satellite terminology)

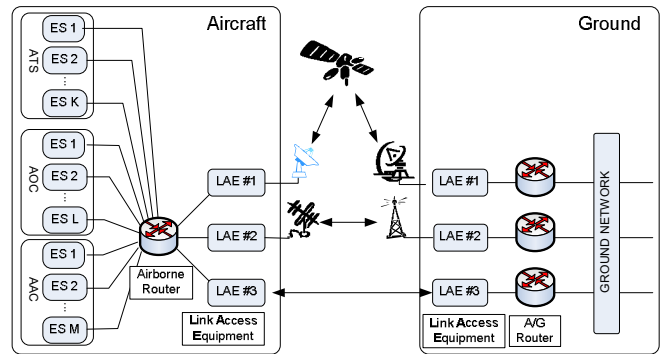
The consequences of applying TCP in this environment are commonly known and include long connection establishment times and long TCP slow start phases (link is used inefficiently for frequent but short sessions). Due to the flow control the throughput on the link is also limited by the round trip delay. Throughput is reduced by unnecessarily entering slow-start and congestion avoidance phases triggered by misinterpretation of packet loss as congestion event (TCP does not distinguish between congestion and packet loss events).

The ATN/IPS includes by definition all types of wireless links. Additionally the functionality of the ATN/IPS should include the possibility to communicate via multiple wireless links dependent on location and equipage. In an ATN environment where the latency requirements have to be strictly met and where a cost efficient usage of the available links gets high economical importance, it is an important topic to investigate which options for using TCP exist and how possible protocols stack architectures can be designed to be efficient and economical. The remainder of this paper is organized as follows: In section II an overview of the envisaged system scenario and the transport layer impact in the heterogeneous aeronautical scenario is given. Section III presents three different alternatives for the protocol stack architectures and discusses their impact on the special demands of ATM communication. The analysis done in this paper focuses on the system and design aspects. Performance investigations using simulations which consider the very short length of most ATC/AOC messages and their irregular occurrence are ongoing at the moment. This might have an impact on the final decision whether a PEP is required for these services, or not. The results presented in this paper reflect thus the actual state of the ongoing work. The final decision for a specific alternative will then also depend on the outcome of the performance simulations. Within section IV the results of the protocol stack analysis done in this paper is summarized. Also an outlook on the ongoing and future work is provided.

## II. SCENARIO IMPLICATIONS

As has been mentioned before, the performance of TCP degrades seriously in wireless environments. While the

negative effects of using TCP in such a wireless environment might be less critical for best effort passenger communication (APC), the situation is different for safety critical Air Traffic Control (ATC) services and Aeronautical Operational Control (AOC) communication since these have hard requirements in terms of maximum delay, integrity and connection establishment time. The detailed operational requirements are summarized in the Communications Operating Concept and Requirements document (COCR) [1]. While the literature contains many approaches on optimizing the TCP protocol to one specific link (e.g. a GEO satellite link) by modification of parameters or introduction of new TCP protocol versions in certain wireless channel environments (such as TCP Hybla [3], F-RTO [4] or TCP Peach [5]), these concepts cannot be directly applied in the heterogeneous ATM scenario. Due to the heterogeneity of the different links in the ATN/IPS network a single TCP protocol cannot work efficiently for all possible links. A tailored solution for one link will underperform when switching to a different link. For the design of a protocol stack a variety of aspects has to be considered including: certification requirements, certification and implementation cost, complexity considerations in the mobile terminals and the fixed ground end systems and the need for worldwide interoperability and compatibility. Figure 1 shows a simplified overview of the envisaged scenario. As can be seen here, several end systems (ES) can be on board the aircraft and each of them can in principle be routed over a different link (under consideration of regulatory requirements and limitations).



**Figure 1 Simplified air/ground communication example**

Each link has its own Link Access Equipment (LAE) which takes care of link and physical layer link access. In the example given in Figure 1 the LAE #1 represents satellite communication, LAE #2 VHF radio and LAE#3 is a generic placeholder for any other applicable link technology. On ground the corresponding LAE is the counterpart of the communication and routes the traffic to and from the ground network. For simplicity passenger communication (APC) is not shown in the figure.

## III. PROTOCOL STACK OPTIONS

In this section several design alternatives for the protocol stack architecture are introduced and explained and their advantages and disadvantages are discussed.

### A. Access Technology Independent Architecture (ATI)

The protocol stack of the Access Technology Independent Architecture (ATI) is shown in Figure 2.

As can be seen in this example, the airborne ES implements a standard protocol stack and is connected via a LAN-like network to the airborne router. According to the routing decision taken in the router, the data are forwarded to the corresponding LAE of the selected link. The link selection within the router will likely be based on multiple attributes and quality metrics of the available links, such as signal strength, measured packet error rate, delay, etc. Thus the needed information has to be somehow signaled from the LAE to the router. Since the architecture envisaged in NEWSKY shall be able to work with any underlying link technology including new upcoming link technologies, a technology independent interface is introduced which serves as common communication interface (Technology Independent Service Access Point, TI-SAP) and is denoted as Media Independent Handover Function (MIHF, [6]) in Figure 2. The TI-SAP has to fulfill several functions. First of all it provides a uniform signaling interface to signal link information such as maximum possible throughput, packet error rates, queue states, etc. in a uniform way to the router which can then base its link selection decision on this. While the technology independent (TI) part interfacing to the upper layers does not change, the Technology Dependent (TD) part of the TI-SAP has to be implemented by each link technology to provide the needed information by the commonly defined primitives.

Moreover the TI-SAP deals with QoS issues such as mapping the technology independent layer 3 queues to the technology dependent layer 3 or layer 2 queues. This is necessary because it cannot be assumed that all link technologies implement the same QoS framework using the same number of traffic queues as the TI part of the network. In this case it is necessary to map the queues from the TI to the TD in an appropriate way, i.e. under consideration of priorities and latency requirements. This functionality is also known as vertical QoS mapping. A second functionality covered by the TI-SAP is the mapping of bandwidth requirements from the TI layers to the TD layers. This is because dependent on which encapsulation procedures are implemented in the different links, the bandwidth demand as experienced in the TI layer 3 might map into different bandwidth demands of the TD lower layers. Finally the TI-SAP functionality includes methods for horizontal QoS signaling among the different network portions, e.g. to negotiate QoS levels.

Two candidate standards dealing with handover and QoS mapping are the IEEE 802.21 standard [6] and the ETSI-BSM standard ([7], [9]) respectively, which can possibly be both used complementary. The definition of all primitives is however out of scope of this work. For the remainder of this work, the MIHF function is thus assumed as generic protocol stack functionality providing the methods mentioned above.

In Figure 2 same colors indicate same protocols, i.e. the TCP protocol residing in the airborne and ground end systems is the same, while the physical and link layers of the on board

LAN, the wireless link and the WAN may differ. This means that the transport layer protocol cannot be adapted to the properties of the underlying link here, resulting in the mentioned inefficiencies. The main advantage of this architecture is the low implementation complexity. Here the ES just has to implement a single TCP protocol which is beneficial for the aeronautical certification and standardization process. A second advantage arises in the context of security. For safety critical ATM communication such as ATS and AOC the application of encryption and / or authentication mechanisms is relevant. One mean to provide encryption and / or authentication is IPSec which is currently also considered in the ICAO WG-I. Since the TCP connection in the ATI architecture is end-to-end, this means that also the IPSec mechanisms can operate end-to-end.

All these advantages come however at the cost of a not optimized transmission and thus a lower link performance. The missing adaptation results in frequent retransmissions, entering congestion avoidance phases and a low total throughput. The efficiency decrease does however not affect connectionless UDP transmissions. On the other hand the drawback of using UDP transmission is that no guarantee can be provided whether the sent ATM datagram really were transmitted and received at the other ES. For safety critical ATC/AOC communication it is necessary to have acknowledgements (ACK) whether a message was received or not. TCP is inherently providing this ACK mechanism. If UDP is used instead of TCP, the ACKs have to be provided by other means. Those could be done by an implementation of a sublayer within layer 3, providing just an ACK mechanism for UDP datagrams without flow control methods as provided in TCP. The drawback of this approach is clearly that the sublayer protocol has to be developed, standardized and implemented in the hardware equipment. Moreover such a protocol extension would be proprietary resulting in higher equipment cost (no reuse of COTS products possible) and a more challenging and costly standardization and certification processes.

Another possibility to acknowledge the correct reception of UDP datagrams is to do this on application layer (AL). Here the correct reception of a datagram can be indicated by sending an application layer acknowledgement back. AL ACKs are often used in current systems to lower the certification cost of the underlying protocol layers. While these mechanisms are currently in operation they are not very efficient. An implementation of automated AL ACKs also means that major modifications have to be implemented in the ESs resulting in higher cost and high standardization and regulation efforts for them.

### B. Performance Enhancing Proxies

To counteract the aforementioned TCP problems for wireless links, another approach is to adapt the TCP parameters for the used link. Such adaptations can include (but are not limited to) large start-window sizes, use of larger data segments, window scaling, receive buffer size, etc. Moreover TCP protocols tailored to the behavior of a link can be used. To accomplish the individual adaptation to the link type, the TCP end-to-end connection is split into a

chain of TCP connections. This splitting is done by so called Performance Enhancing Proxies (PEP). An application example of this architecture is shown in Figure 3. As can be seen here, the TCP connection is not directly end-to-end with the same protocol as in the ATI architecture, but the TCP connection is split at the airborne and air/ground routers which serve as PEP gateway. This means that e.g. for the LAN connection from the ES to the LAE a standard TCP protocol can be used which performs well for this segment. In the LAE, the TCP connection is locally responded and depending on the selected link another TCP connection optimized for this link is established. On the ground LAE the TCP connection tailored to the link is responded and replaced by another TCP connection using standard TCP protocols. As gets clear from Figure 3, it is possible to apply PEPs only to certain links, while others do not have to implement PEPs. The main advantage of this architecture is clearly that the different links are used at the best possible performance, minimizing for instance end-to-end delay and the number of retransmissions for connection oriented transmissions. Also with this architecture the ES do not have to implement specific TCP versions or TCP parameter sets, which in turn allows for the reuse of COTS products and does not rise the need for expensive standardization needs of the ES. Another advantage that this solution has is that it is possible to have several connections over different links running at the same time with TCP optimized for each link type. For satellite communication the usage of PEPs is also common and well proven technology. For aeronautical standardization and certification procedures this might prove advantageous.

On the other hand PEPs may have problems in accelerating the TCP connection. One major issue is the loss of context between two PEPs. Due to mobility aspects, the correspondent PEP might change when switching the connection. This could mean that a PEP is e.g. not receiving the TCP FIN message indicating the end of the TCP transmission or that the new PEP does not receive a TCP SYN message. Using PEPs in these conditions would require that connections can be closed and started without full knowledge of the context or that the context has to be signaled from the old to the new PEP. Additional problems which occur in combination with mobility are the use of tunnels and security, change of address and loss of data during mobile node mobility. When using IPsec to encrypt safety critical communications an additional problem is that the TCP header fields are either encrypted or digitally signed (and thus not modifiable). In this case a PEP cannot accelerate the connection since it either cannot read the encrypted content or it is not allowed to modify it since the packet would then be discarded by the receiver.

The problem with IPsec and PEPs can be eased by splitting the IPsec connection at the same points as the TCP connection. This however means that the service providers running the PEPs get full access to the plain text content of the transmission. For a variety of reasons this might not be desirable. For instance an airline would not want its fuel consumption statistics to be public to competitors. A trusted relation to the service provider to treat the content

confidential would thus be required here. The end-to-end IPsec connection is then split into a chain of trusted connections. Whether this possibility is interesting from an operational point of view is open at present and something to be addressed in the aeronautical community.

Another option to deal with the security problematic in context with PEPs is to apply multi-layer IPsec which allows the degree up to which intermediate nodes get access to the content of a transmission. Another attractive solution would be to apply application layer or transport layer security mechanisms instead of IPsec. In this case the TCP acceleration will be possible while the application payload remains hidden to the service providers.

Regarding implementation, the LAE will have a higher complexity than in the ATI architecture mentioned before. While the ESs are not affected (PEP functionality is transparent to the ES), the LAE has to implement the PEP functionality. The transparency for the ES is especially important for APC since the passenger ESs will not be modifiable and will also not implement different TL protocols tailored for a variety of wireless links.

### *C. Protocol selection in the ES*

The third protocol stack solution is illustrated in Figure 4. The main drawback of the PEP architecture explained before is that TCP connections are split which raises the mentioned mobility and security problems. A third possibility to increase the link efficiency without splitting the TCP connection is to implement different TCP protocol versions in the ES and select the TCP protocol dependent on the link which is used for a communication.

In this case the TCP connection would be end-to-end without the need to use PEPs. Since the ES takes the decision of which TCP version shall be used for the connection it is also necessary to do the link selection in the ES or to signal to the ES which link has been selected by the router. This signaling overhead and the implementation of the signaling methods is a disadvantage of this solution. Since the TCP connection is end-to-end it is obvious that the connection can only be optimal for one of the involved links along the route. If for instance the total communication path consists of an airborne LAN segment, an aircraft-to-aircraft link followed by a satellite connection, the TCP protocol can only be optimized for one segment in the chain. With regard to this it can be expected that this solution performs worse than the PEP architecture but better than the ATI architecture. This is because in this architecture the TCP version can be selected based on the most demanding link in the connection. An advantage is that the complexity of this architecture is smaller for the intermediate nodes compared to TCP splitting. COTS products could be reused for the A/G routers and standardized protocols can be implemented in the ES. While complexity can be saved in the LAE and routers, additional complexity occurs in the ES which now have to implement several TCP versions. While the implementation of different TL protocols might be possible for ATC/AOC ESs this will not be the case for APC where passengers carry their own equipment. The implementation of different TL protocols and signaling protocols is thus not

realistic and makes this alternative unattractive for APC. Even the certification process for the ATC/AOC ESs can be expected to get much more difficult, time consuming and expensive than in the ATI case. A dedicated signaling protocol must be defined to signal the selection of a link to the ES. Also the ESs on the ground have to implement all possible TCP versions. Finally the introduction of a new link technology which requires a new dedicated TCP protocol would require that all ESs have to be changed and have to implement this new protocol. Considering that each ES worldwide would be affected by this, this is a clear argument against this solution

#### *D. Evaluation of alternatives*

The decision of which protocol stack architecture is the most suitable one for application in an ATN/IPS network is a tradeoff driven by economical aspects, certification effort and technical efficiency. While solutions such as the ATI keep certification and economical cost low, the technical efficiency can seriously suffer for some links and applications. A plain ATI solution would thus seriously reduce the overall system performance, especially for critical links like GEO satellites. Other solutions like the presented PEP architecture can significantly improve the technical performance but require a higher implementation complexity to address mobility and security problems resulting in higher complexity and eventually cost. Finally the solution proposing a protocol selection in the ES tries to unite the technological efficiency of PEPs without having the mobility and security problems. But the main drawback of this solution is the certification effort and cost and the need to modify all ES to have a common and interoperable worldwide system. The high effort for certification of the ESs and the problems occurring when introducing a new link requiring a dedicated protocol implementation in the ES are a clear argument against this approach. Summarizing all the advantages and disadvantages as explained before the most attractive alternative seems to be a hybrid protocol stack providing ATI functionality for links which do not suffer from regular TCP protocols while PEP can be implemented for links which require performance enhancement. This hybrid solution remains transparent to the end user, so no modifications in the ESs have to be made. The detailed definition of methods to address the mentioned mobility issues with PEPs still have to be defined and are subject for further work. To determine for which services and links PEPs are required, performance simulations considering the ATC/AOC and APC traffic characteristics are currently ongoing.

#### IV. CONCLUSIONS

In this work the fundamental requirements of a protocol stack design for ATM have been explained. Three different

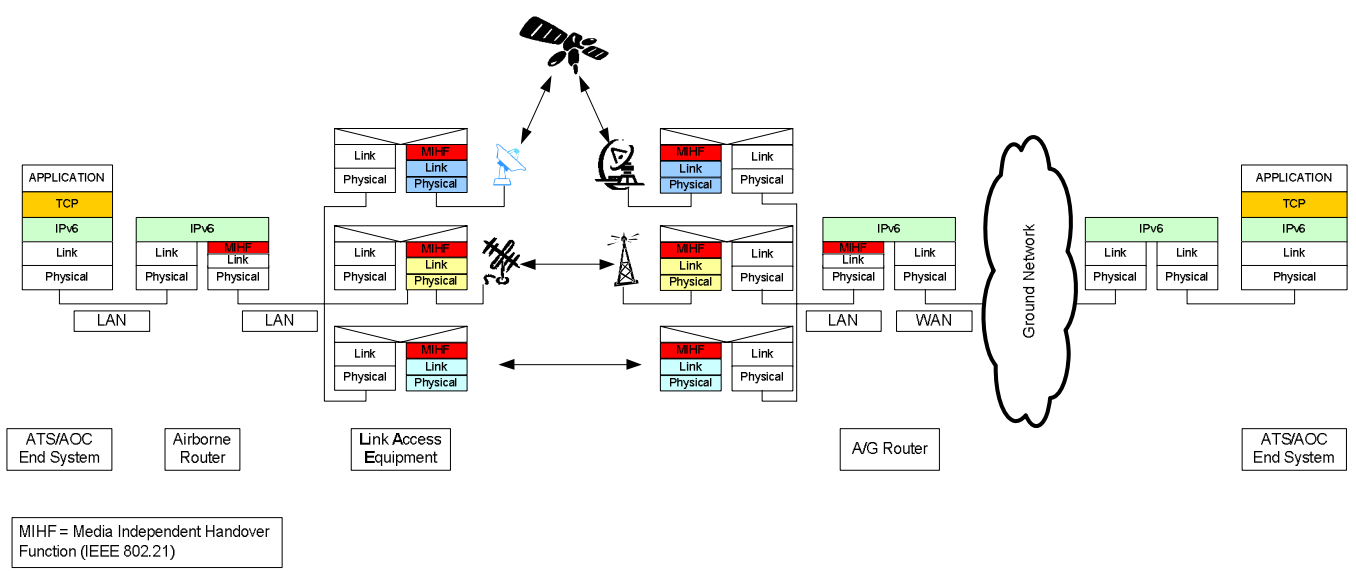
protocol stack alternatives have been investigated and their advantages and disadvantages with respect to the special ATM have been discussed. It was shown that a protocol stack architecture which operates independently of the link technology cannot efficiently work for all wireless link types. The drawbacks of an architecture enhancing the performance of TCP by using PEPs with regard to encryption and mobility have been explained. Finally the problems of moving the link- and protocol selection to the ES have been presented. The final recommendation for a protocol stack architecture will in the end also strongly depend on the outcome of the performance simulations under consideration of the special ATC/AOC traffic profile. While PEPs are an interesting solution to the TL performance problems occurring in a heterogeneous ATM environment, the special nature of ATC/AOC communications, represented by irregular and small datagrams rises the question whether PEP acceleration will be needed also for these services or only for APC. As conclusion (with respect to the actual work status) a hybrid solution appears to be very promising regarding economical benefit, certification effort and technological efficiency. This hybrid solution allows ATI for links not requiring the adaptation of the TCP protocol and leaving the possibility to use PEP techniques for links needing a TCP performance enhancement to make efficient usage of the link.

#### V. ACKNOWLEDGMENTS

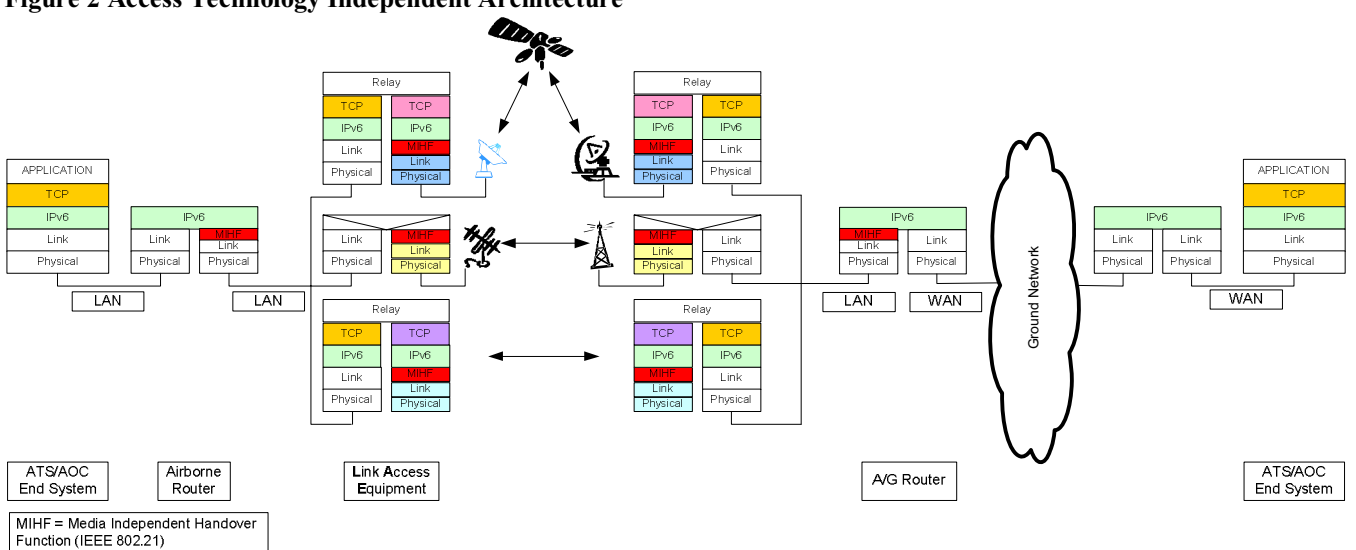
The authors would like to thank Christian Bauer for fruitful discussions on the topic especially regarding security issues.

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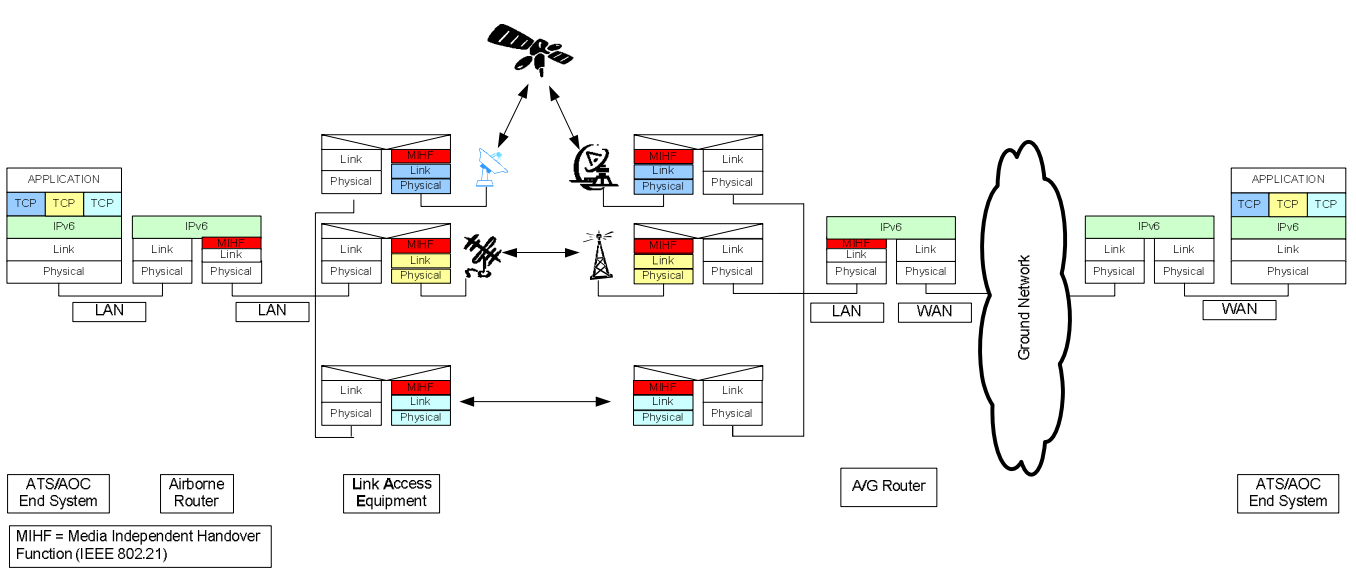
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**Figure 2 Access Technology Independent Architecture**



**Figure 3 Application example of Performance Enhancing Proxies**



**Figure 4 Transport layer protocol selection in the end systems**