Unidirectional Lightweight Encapsulation: Performance Evaluation and Application Perspectives

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***Abstract*—Multi Protocol Encapsulation (MPE) is today the dominant method for encapsulating IP data into the MPEG-2 Transport Stream so they can be conveyed over digital television platforms (DVB or ATSC). Unidirectional Lightweight Encapsulation (ULE) is a new alternative to MPE, providing simplicity, efficiency and configurability. This paper presents the principle and benefits of ULE, approaches the issues associated with its adoption and compares it against MPE through extensive performance measurements in a fully functional testbed under IPv4 and IPv6 load. It also proposes, implements and demonstrates the combination of MPEG-4/H.264, IPv6 and ULE as the most efficient and flexible protocol stack for next-generation transmission of digital video over Digital Television networks.**

***Index Terms*—Data broadcasting, IP-over-MPEG-2, MPE, ULE.**

I. Introduction

ALMOST all contemporary digital broadcasting systems, including the DVB and ATSC family of standards, are using the MPEG-2 Transport Stream (TS) [1] as the format of baseband data, organized in a statistically multiplexed sequence of fixed-size, 188-byte Transport Packets. Initially intended to convey MPEG-2 encoded audio and video streams, the MPEG-2 TS was eventually used also for the transport of IP traffic, with the adaptation method introduced in [2] and named as Multi Protocol Encapsulation (MPE). The adoption of MPE accented the role of DTV platforms as access networks for IP-based broadband data and multimedia services [3]. Broadcasters have the potential to use a part of the capacity of the broadcast channel to include unicast or multicast IP traffic along with the audiovisual streams [4]. What is more, state-of-the-art broadcasting technologies, such as DVB-H or DVB-S.2 are IP-oriented and actually expected to carry exclusively IP data rather than MPEG-2 content.

This tendency towards the convergence of the worlds of digital broadcasting and IP-based telecommunications [5], [6] has initiated research efforts towards a more efficient and flexible encapsulation protocol. The IP-over-DVB (ipdvb) working group of IETF proposes an improvement of MPE, namely the Unidirectional Lightweight Encapsulation (ULE, formerly Ultra Light Encapsulation) [7]. In comparison to MPE, ULE offers simplicity, improved efficiency, native IPv6/MPLS (Multi Protocol Label Switching) support and greater flexibility via optional Extension Headers. The new protocol has recently been adopted by IETF as a "Request for Comments" (RFC) document. While ULE is an upcoming technology and is supported in only few commercial products, its benefits show that it is very likely to replace MPE in the next years.

This paper presents an in-depth overview of MPE and ULE techniques and compares their efficiency through extensive performance measurements carried out in a real DVB-based testbed. Section II analyses the encapsulation procedure for each protocol and outlines the benefits of ULE over its predecessor. Section III discusses the issues which arise from the full adoption of ULE in DVB networks, suggesting possible solutions. Section IV describes the implementation of the testbed, presents the methodology which was followed and analyses the results of the performance measurements conducted under several scenarios including IPv4 and IPv6 traffic. It also proposes a protocol stack based on MPEG-4/H.264, RTSP (Real-Time Streaming Protocol), IPv6, ULE, MPEG-2 and DVB-S specifications and demonstrates its use for next-generation digital television networks. Finally, Section V concludes the paper.

II. An Overview of Encapsulation Protocols

A. The Principle of IP-Over-MPEG-2 Encapsulation

In order that IP datagrams can be conveyed over a digital television network whose data format follows the MPEG-2 TS specification, they have to be encapsulated in MPEG-2 Transport Packets (TPs). The latter have a constant length of 188 bytes, so a fragmentation (and reassembly) procedure is required. The first stage of the encapsulation process is the framing of the datagram with the encapsulation protocol header and the CRC/checksum. In this context, the datagram has the role of the Protocol Data Unit (PDU) and the resulting framed data can be named as Sub Network Data Unit (SNDU).

ETSI dealt with the data encapsulation issue by standardizing four methods [2], namely Data Piping, Asynchronous Data Streaming, Synchronous Data Streaming and Multi Protocol Encapsulation (MPE). The latter was proposed as the most suitable method for conveying IP datagrams and was soon adopted by all IP-to-MPEG-2 Gateways.

B. Multi Protocol Encapsulation

In MPE, network layer datagrams (PDUs) are framed within blocks called datagram_sections (SNDUs). The structure of the latter is compliant to the general DSMCC_section (Digital Storage Media Command and Control) format as this was defined in [8] for the transport of private data over the TS. This framing process includes the addition of the datagram_section header in the beginning of the section (before the IP datagram), and a 4-byte CRC or checksum at the end calculated over the entire datagram_section. Among others, the datagram_section

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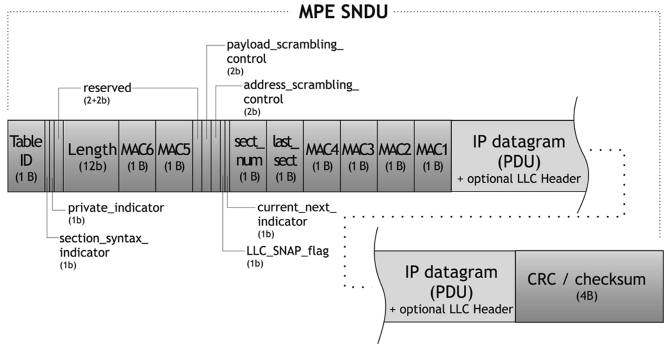

Fig. 1. Structure of datagram_section (MPE SNDU).

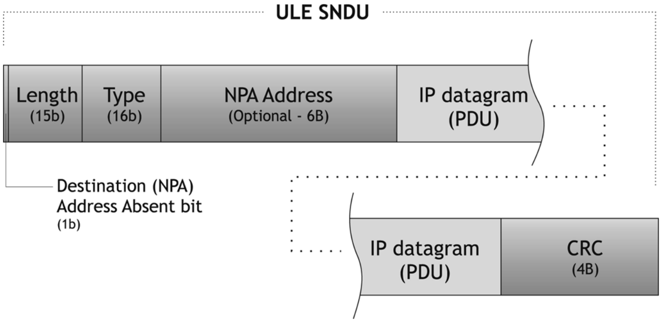

Fig. 2. Structure of ULE SNDU.

headers contain fields declaring the length of the section, the scrambling status and the MAC address of the receiver. Several MPEG-defined fields are also present, as shown in Fig. 1.

Once formed, the datagram_section (SNDU) is split into several fragments and transferred to the payload of Transport Packets. If the length of the SNDU is not an integer multiple of the TP payload (184 bytes), the encapsulator module has the option of either padding the rest of the last TP with stuffing bytes (“padding”), or beginning a new SNDU in the remaining area (“packing”).

The main drawback of MPE is the inclusion of several MPEG-specific fields in the section header, which in fact can as well be omitted. Moreover, the declaration of the receiver MAC address, (which is not always necessary, since the TS is itself a sub-network layer and the traffic is already divided in logical channels) is mandatory in MPE, adding an overhead of 6 more bytes.

Another issue is the absence of the declaration of type of data contained in the SNDU. MPE offers the option of either having a pure IP payload (no discrimination between v4 and v6), or carrying the data with an LLC/SNAP (Logical Link Control/Sub-Network Access Point) header. So, there is no uniform representation of the type of the encapsulated data, as it exists e.g. in Ethernet framing with the Type field.

C. Unidirectional Lightweight Encapsulation

ULE was designed with the aim of making the encapsulation process as lightweight as possible, without sacrificing flexibility [9], [10]. It follows the approach of “data piping” i.e. directly mapping the PDU into the TP payload, adding only a small header. ULE header contains just a Length field which declares the length of the SNDU, and a Type field which has the same functionality with that of Ethernet i.e. it declares the type of the payload. Thanks to the Type field, ULE provides native support for state-of-the-art network protocols, such as IPv6 and MPLS. Depending on the value of this field, the PDU can be an IPv4 datagram, an IPv6 datagram, an MPLS- or even a whole bridged MAC-frame.

The ULE header can also include a 6-byte destination address corresponding to the receiver’s Network Point of Attachment (NPA). The NPA address (which can correspond to the receiver’s MAC) is used to uniquely identify a receiver in the MPEG-2 transmission network and is mandatory only in the case that the PDU is to be processed by a receiver-router, which will further forward it to its final destination (sharing of the received DTV stream among multiple terminals). If this is not the case and the data is directly received by the destination terminal, this field can be omitted and filtering can be performed at IP level.

If there is additional SNDU-level signaling which cannot be carried in the existing header fields, ULE provides the option of adding one or more Extension Headers after the standard header and before the PDU, carrying the data which are needed.

Finally, a CRC-32 tail is appended (as in MPE) to ensure proper reception and synchronization. Fig. 2 shows the structure of the ULE SNDU. The framing has become as lightweight as possible (compare with Fig. 1), retaining only the necessary fields for proper de-encapsulation and forwarding of the IP datagram.

After framing, the ULE SNDU is mapped to the payload of MPEG-2 Transport Packets. In the case that the SNDU length is not an integer multiple of the TP payload, one of the aforementioned techniques of Padding and Packing can be employed.

A simple observation of Fig. 1 and Fig. 2 is sufficient to demonstrate the simplicity introduced by ULE. By reducing the framing fields only to the necessary ones, ULE saves bandwidth and processing time at the encapsulator. Moreover, the exclusion of the MAC address field from the mandatory components of the SNDU, ULE restricts the filtering at the receiver to the network layer only (L3 filtering) and eliminates the need for an IP-to-MAC association table in the encapsulator, which would need additional resources in order to be created and maintained. In the case of MPE, the encapsulation of each datagram requires a lookup in the aforementioned table in order to specify the MAC address corresponding to each IP destination.

D. Efficiency Analysis and Comparison

A principal characteristic of any encapsulation protocol is its framing efficiency, i.e. the ratio of useful bytes over total bytes. From this figure, one can deduce how much overhead is inserted by the encapsulation process. In personal communication networks and especially in circuit-switched access solutions, framing efficiency is of course important but not so crucial, since each user is given a certain amount of bandwidth, dedicated to him/her. In the case of broadcast networks, such as digital television systems, the downlink bandwidth is shared among all users and thus it is much more precious. It is therefore very important that the available capacity is exploited at its maximum, and not wasted in unnecessary overhead and/or stuffing.

In the case of IP-over-MPEG-2 networks, the efficiency factor can be defined as the ratio of the bit rate of a given IP data stream to the rate at MPEG-2 TS-level required to convey this stream:

$$\alpha = \frac{IP\ rate}{TP\ rate}$$

which can be expressed more analytically in terms of field lengths shown in the equation at the bottom of the page.

This ratio is not constant, but depends mainly on the IP datagram size and the encapsulation method used. In the denominator of the expression of α, the MAC/LLC/SNAP header must also be added in the case of bridged data, i.e. when the entire MAC frame is encapsulated. Furthermore, in the case of Padding, the amount of stuffing bytes which are used to fill the last TP carrying the SNDU must also be taken into account.

It is evident that the efficiency factor increases with greater datagram lengths. The following graphs present the results of an analytical approach regarding the efficiency factor of MPE and ULE as a function of packet length. Various scenarios were considered:

- MPE SNAP: MPE with SNAP/LLC encapsulation
- MPE IP: MPE without SNAP/LLC (IP datagrams only)
- ULE Bridging: ULE with the whole MAC frame encapsulated (data bridging)
- ULE IP, NPA: ULE with IPv4/IPv6 payload, including the NPA address (mandatory for link sharing)
- ULE IP: ULE with IPv4/IPv6 payload only

Each scenario was examined with both the Packing and Padding procedure for treating partially filled Transport Packets. The results were derived by modeling based on the aforementioned expressions of α and are depicted in Fig. 3. A similar approach is followed in [11]

It is clear that the Padding method, although more easy to implement and more widely adopted, results in a significant waste of bandwidth, independent of the encapsulation protocol used. The efficiency fluctuates with packet size, is the same for both protocols at all modes and is maximized when the SNDU fits exactly into an integer number of transport packets. With the Padding option enabled, even a protocol with less overhead than ULE would perform the same, since the gain from the lightweight framing is always wasted in the stuffing bytes. The Packing approach is much more efficient, and reveals the differences among the various encapsulation methods. These differences are most observable at small packet lengths (up to 200 bytes), where the framing overhead represents a significant percentage of the SNDU length. For small packets, the use of ULE instead of MPE for plain IP encapsulation (i.e. excluding MAC/LLC headers, which are rarely necessary) can result in gain up to 40% in capacity. An additional benefit is the saving of processing power both in the encapsulator and the receiver, achieved by avoiding the complexity of the MPE header.

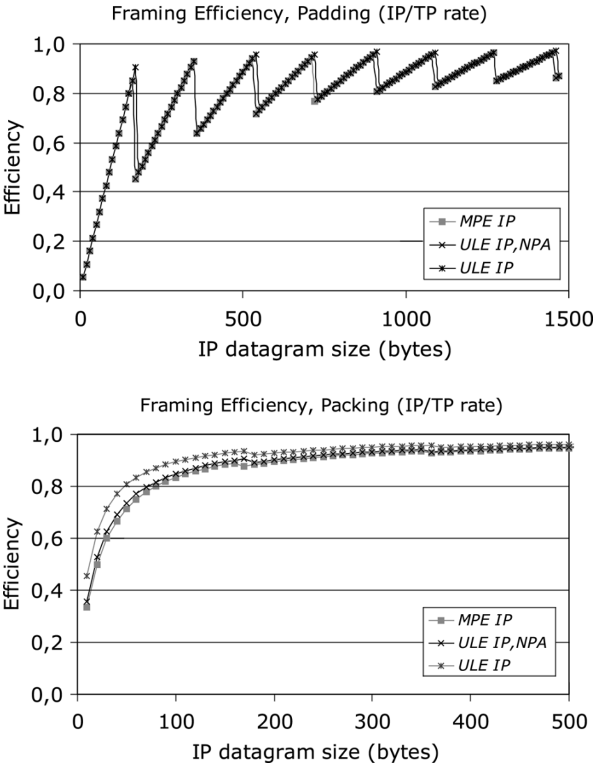

Fig. 3. Modeled efficiency of various MPE and ULE options, in padding and packing mode.

III. ULE APPLICATION PERSPECTIVES AND ISSUES

As shown in the previous section, ULE indeed provides a simpler and more effective alternative to MPE. However, MPE has already been world-widely adopted in both IP/MPEG-2 Gateways and decapsulators/receivers, as being the only IP-to-MPEG-2 encapsulation protocol for almost a decade [12]. On the other hand, ULE, which is soon to reach RFC stage but is still under standardization, is only supported by a few Gateway manufacturers and there are still several ULE-enabled modules which are in the experimental phase and have not been commercially released. An important step towards the adoption of the new protocol was the inclusion of a ULE processor/decapsulator in the Linux kernel (version 2.6 onwards) as part of the Linux DVB API. Another key point which can speed up the adoption of ULE is its native support of multiple network protocols, including IPv4, IPv6 and MPLS-tagged datagrams, which are bound to be exploited in terrestrial and satellite networks. Being an adaptation layer, ULE promises to bring the benefits of IPv6, including huge address space, smooth routing, mobility and increased security, to future IP-over-DTV

$$\alpha = \frac{(IP\ datagram)}{(TP\ header) + (SNDU\ header) + (IP\ datagram) + CRC}$$

networks. These benefits, especially mobility and security, are crucial for IP networking based on digital broadcast platforms which are expected to support a large number of receivers listening to the same stream and performing handovers. For backwards compatibility reasons, ULE provides the option of IPv4 and IPv6 coexistence, even within the same MPEG-2 logical channel.

On the other hand, there are several issues which arise from the perspective of migration towards ULE. The following paragraphs focus in the DVB family of standards and discuss such migration issues.

A. *Migration to ULE in DVB-S Networks*

Encapsulated IP datagrams in DVB-S streams are nowadays a popular solution for broadband satellite Internet access [13], [14]. The migration to ULE could result in a significant amount of bandwidth saving, which is indeed crucial when it comes to expensive satellite capacity. The fact, however, is that MPE is the dominant protocol in satellite DVB receivers. The support of both protocols in new devices raises the issue of the discrimination of the encapsulation method used in each logical channel of the DVB multiplex. Since no alternative to MPE has practically ever existed, DVB signaling structures do not have a dedicated field for the declaration of the encapsulation protocol. Thus, a dual-protocol receiver is not a priori aware of the format it should expect after depackaging the MPEG-2 transport packets. An auto-detection process could be a solution, but could sometimes be misleading. The protocol type could be declared via a signaling mechanism, such as the INT (IP/MAC Notification Table) which is defined in [2] and contains information about the data streams contained in the MPEG-2 multiplex.

Regarding DVB-S.2 [17] the newly standardized successor to DVB-S, the introduction of the "Generic Stream" (GS) option by the DVB-S.2 specification is expected to provide a means of directly transmitting IP datagrams without the need for an underlying MPEG-2 TS layer. However, this option is not yet directly applicable and at the time is not supported by commercial products. It seems that, even in the case of DVB-S.2, the need for an IP-to-DVB protocol will continue to exist in the near future.

B. *Migration to ULE in DVB-T Networks*

By gradually replacing their analog predecessors across Europe but also around the world, terrestrial DVB networks are bound to be used for data access in addition to DTV programs distribution. Focusing in mobile use, the scenario of DVB-T/cellular synergy seems very attractive [15]. The adoption of ULE in DVB-T platforms will maximize efficiency and reduce wasting of the UHF spectrum. Moreover, in the terrestrial case, the single-user-per-receiver scenario is the most probable one (than having multiple users sharing a single connection) due to the low price and easy, "anytime-anywhere" use of DVB-T receivers. This means that the NPA address field of the ULE can be omitted, further increasing the efficiency in comparison to MPE, where the inclusion of the MAC address in the header is unavoidable yet needless.

Again, as stated in the previous paragraph, a mechanism for discriminating between MPE and ULE streams must be employed. However, since IP-over-DVB-T data communication is not yet widespread even in countries where DVB-T penetration is high, the migration to ULE is expected to be much simpler than in the satellite case.

C. *Migration to ULE in DVB-H Networks*

DVB-H (DVB for Handheld) is a newly standardized enhancement to DVB-T which focuses on IP data transmission over the mobile terrestrial channel [16] using the MPEG-2 TS as baseband format. Since DVB-H networks, either as new infrastructures or upgraded versions of DVB-T platforms, are currently under development, the broadcasters do not have to cope with already deployed terminals, having to be enhanced in order to support ULE. However, there are certain technological innovations of DVB-H which have been based on MPE and the adoption of a new encapsulation protocol will require a few minor adjustment procedures.

First, there is MPE-FEC (forward error correction for multi protocol encapsulated data). In order to provide the capability of not only stronger, but also selective error protection of the transmitted data, the specification gives the option of organizing multiple datagrams in a table called "MPE-FEC frame" in an interleaved scheme, column by column, and protecting each row of the table with a Reed-Solomon extension. Then, each column of the table, along with the RS overhead, is transmitted encapsulated within MPE sections.

The DVB-H specification also includes the process of so-called "time-slicing" as a mandatory extension. Since the DVB-H system is targeted to portable/handheld devices, which are assumed to be battery-powered, the Time Slicing technique organizes the data within the MPEG-2 multiplex into a strict TDM scheme, with each IP stream being transmitted into bursts. Combined with proper signaling, the Time Slicing feature allows the receiver to activate its demultiplexing/decapsulating/IP processing subsystem only when it is expecting a burst with data destined to it. This selective activation has been shown to greatly contribute to power saving, thus extending the battery time of the DVB-H receiver. Again, as with MPE-FEC, Time Slicing uses the MPE structure. The "delta-t" value, accompanying each SNDU, defines the difference in time between two successive bursts on the data stream.

In order to convey signaling related to FEC and Time Slicing, DVB-H uses six bytes in the MPE header. Two of them declare the position of the following PDU within the FEC table and the remaining four carry the "delta-t" value. For ULE to be used in DVB-H networks with MPE FEC and Time Slicing enabled, these six bytes must be added prior to PDU payload. This addition can be performed by using the Extension Header option of ULE for adding proprietary signaling after the standard ULE header. Even with this overhead (equivalent to enabling the 6-byte NPA option), ULE is still more efficient than MPE, although the difference has now become marginal (In Fig. 3, compare the "ULE IP, NPA" and "MPE IP" curves).

IV. DATA BROADCASTING TESTBED AND PERFORMANCE EVALUATION

In order to evaluate and compare the performance of the two protocols in a real environment, a fully functional DVB-S

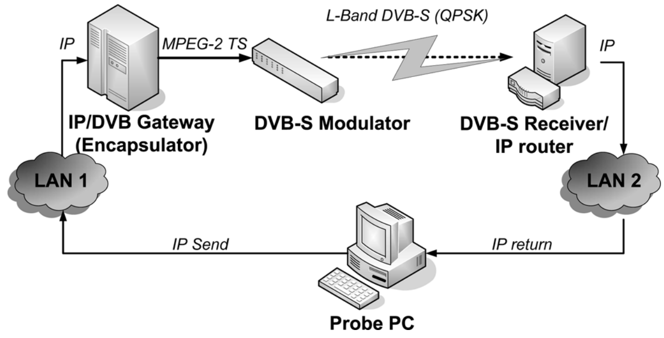

Fig. 4. DVB testbed for protocol evaluation.

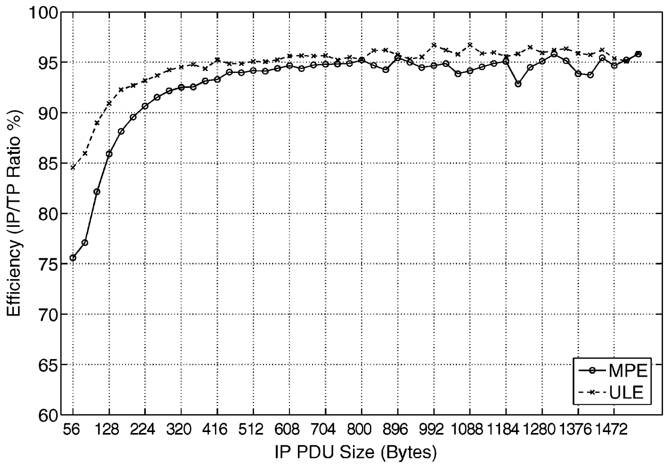

Fig. 5. Measured framing efficiency for ULE and MPE, IP-only mode, packing enabled.

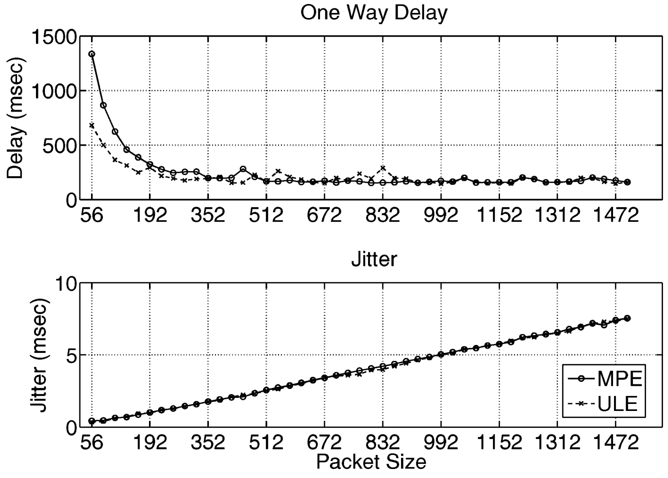

Fig. 6. Indicative one-way delay and jitter for a 3 Mbps IP stream.

testbed was implemented in a closed-loop form (Fig. 4). A Newtec DVB-S modulator operating at 17 Mbits/sec generates a DVB-compliant RF signal in the L-band. This signal feeds directly a DVB-S data receiver/router comprising of a Linux workstation equipped with a satellite interface. The receiver/router incorporates MPE and ULE decapsulation support at kernel level based on the linuxtv implementation [18]. IP-to-DVB encapsulation is undertaken by a commercial IP Gateway, with MPE (full) and ULE (experimental) support. The IP Gateway captures the IP traffic, filters it according to rules set by its administrator, and generates the DVB-compliant MPEG-2 Transport Stream to be fed to the Modulator.

The performance measurements are conducted via a Probe PC which is linked to both ends of the DVB-S chain via separate LANs. The Probe PC acts both as source and sink for the generated IP traffic. It is equipped with two network interfaces, one for sending the IP stream to the Gateway for encapsulation and transmission and a second for capturing the IP data forwarded by the router/receiver. This single host is used for sending, receiving, and measuring network-level characteristics such as delay, loss or jitter. This approach eliminates the need for synchronization and the possibility of sync errors and CPU clock skew between different machines which could affect the measurements. The IP data stem from a traffic generator or a video server and follow a circular route via the Gateway, modulator, receiver until they return to their point of origin.

A first set of measurements aims to evaluate the effect of PDU (IP datagram) size in the performance and efficiency of the encapsulation process. At the Probe PC, a 3 Mbps IPv4/UDP stream is generated by mgen [19] using various datagram sizes, spanning from 28 to 1500 bytes. The "IP-only" encapsulation mode for both ULE and MPE is used, along with the Packing technique. The IP/TP ratio for each case is calculated on a per-second basis from the logs of the "bytes received" and "bytes sent" counters of the Gateway. The results are depicted in Fig. 5 and are very close to the theoretical curve presented in Section II.

In order to emphasize the effect of the encapsulation process on network parameters, such as one-way delay and jitter both in the MPE and ULE case, a marginal situation is chosen: a 3 Mbps IP stream is conveyed over an MPEG-2 logical channel with a bandwidth limit of 3.3 Mbps, so the encapsulation chain is driven to congestion. The use of small IP PDUs results in higher bandwidth requirements, due to the decreased framing efficiency. At the Probe PC, both the outgoing and incoming traffic are dumped to disk, and the contents of the dumpfiles are subject to off-line analysis. The one-way delay and the average packet jitter are calculated for several datagram sizes (Fig. 6). As expected, delay is higher in smaller packets, as the relatively higher overhead accumulates more packets in the FIFO buffer of the encapsulator. Again, ULE seems to achieve better results, especially in small sizes. This is not the case with network jitter. The latter increases linearly with packet size and is the same for both protocols. It is important to note that these two values, delay and jitter, are only indicative since they depend on several factors such as encapsulator efficiency, MPEG multiplexing strategy, stuffing procedure at the modulator, architecture and efficiency of the receiver/decapsulator.

The results derived up to now are based upon constant-packet-size, constant-rate dummy IP traffic stemming from a traffic generator. However, it is interesting to study the behavior and especially the efficiency of both protocols under a more realistic scenario. It is anticipated that, after the gradual replacement of MPEG-2 as a video encoding standard with much more bandwidth-efficient specifications (MPEG-4, H.264), the perspective of IP video streaming over digital television platforms

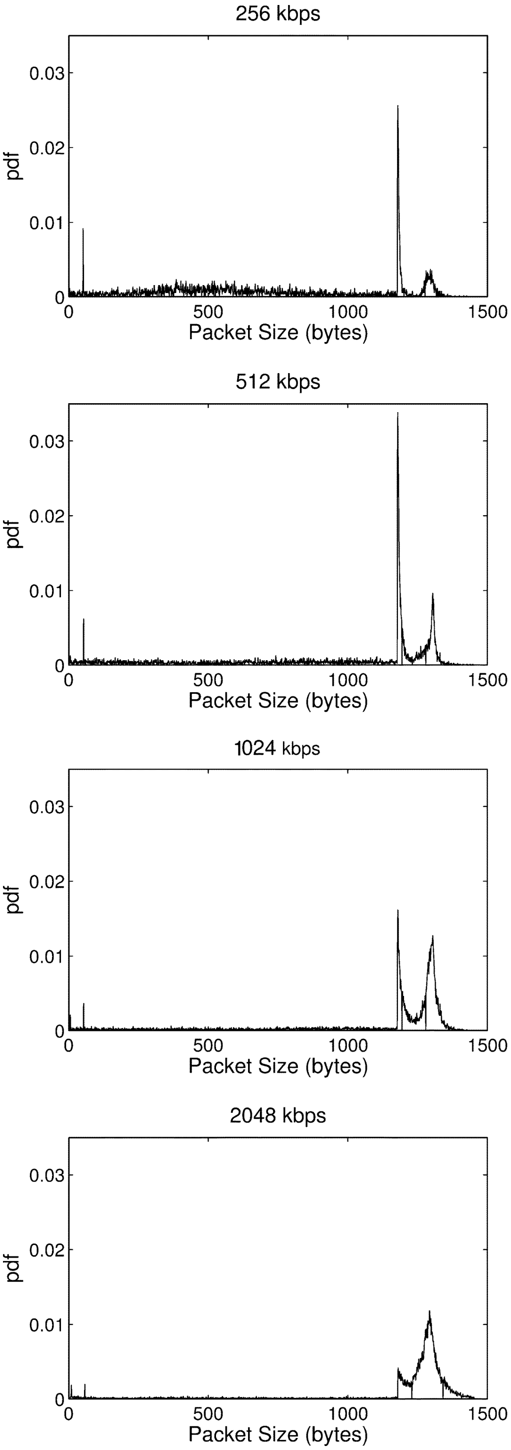

Fig. 7. IPv6 datagram size distribution for the MPEG-4 video streams at various encoding rates.

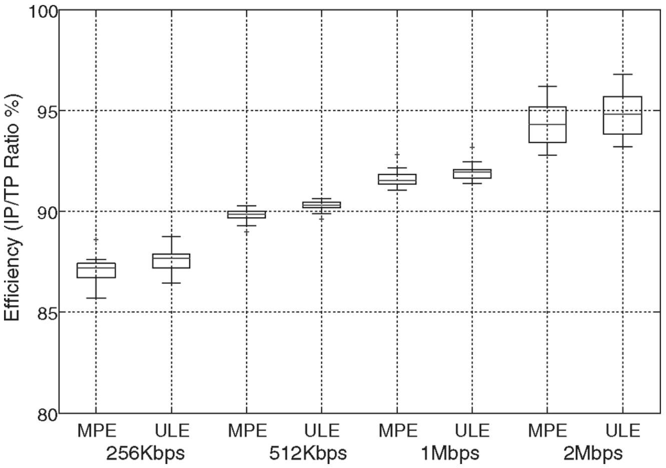

Fig. 8. Framing efficiency for the various video streams.

will provide an attractive alternative to traditional MPEG-2 digital television. MPEG-4 and H.264/AVC video streaming over IP is expected to be the main IP-based application for contemporary terrestrial and satellite DTV platforms. Thus, a realistic scenario would be to test the whole encapsulation procedure for conveying an IPv6 video stream served in real time by a video server. For this purpose, a 3-minute video clip, containing representative scenes of various spatial and temporal activity levels, was encoded with CIF resolution at 256, 512, 1024 and 2048 kbps using the latest ISO MPEG-4 codec with key frame period equal to 24. The aforementioned clips were streamed over IPv6 by an IPv6-enabled video streaming server making use of the Real Time Streaming Protocol (RTSP). It was shown in the previous sections that protocol framing efficiency is dependent upon PDU size. It is thus important to know the IP datagram size distribution for the various encoding rates. The size histograms were derived from an off-line analysis of the dumped real-time video streams and are shown in Fig. 7.

The video streams undergo the encapsulation/transmission process using both MPE and ULE. At the encapsulator, Instantaneous framing efficiency is measured at 1-second intervals for the whole duration of the clip (3 minutes). The results are depicted in the boxplot of Fig. 8 which shows the median efficiency for each case along with the 50% area (boxes) and the min/max values. Since packet sizes are mostly above 1000 bytes, the difference in efficiency is observable yet marginal. As seen in Fig. 7, higher encoding rates result to greater datagram sizes which reduce the percentage of the framing overhead over the whole SNDU.

Regarding efficiency, in the case of IPv6 video streaming, ULE introduces a slight improvement over MPE. Its major advantage, in this case, is it native support for IPv6, via the explicit declaration of the PDU type carried in the Type field. This feature allowed the receiver to automatically detect the payload type and forward it to the IPv6 stack. This was not the case with MPE, in which the IP version is not declared, and a proper reception required tedious and manual configuration of the receiver. It can be thus deduced that, at the moment, the MPEG-4/H.264-over-IPv6-over-ULE can be seen as the most flexible and efficient method of SD- and HD-video streaming over a Digital Television platform.

V. CONCLUSION

Given the global tendency of all communications being carried over the Internet Protocol, IP-enabled digital television networks (DVB/ATSC) are expected to play a major role as broadband data access solutions, especially in the wireless/mobile sector. This paper compared Multi Protocol Encapsulation, the dominant protocol for encapsulating IP datagrams within an DTV-compliant MPEG-2 stream with Unidirectional Lightweight Encapsulation, an enhanced yet lightweight protocol designed to suit the needs of IP-over-MPEG-2 broadcasting. ULE features simplicity and improved efficiency, native support of state-of-the-art network protocols (IPv6/MPLS) and flexibility provided by the optional Extension headers. The paper also discussed the issues associated with the adoption of ULE in existing DVB systems, both satellite and terrestrial. A comparative performance evaluation followed, carried out through modeling and also through real-life tests in a dual-protocol, fully-functional DVB testbed. A state-of-the-art solution for efficient DTV broadcasting was proposed and implemented, using MPEG-4/H.264 over IPv6 and ULE. The results showed that the efficiency, simplicity and configurability introduced by ULE gives it a significant advantage over its predecessor and strengthens the perspective of its wide adoption, especially in the cases where the cost of migration is negligible.

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