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Context-aware hybrid satellite-terrestrial broadband access

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Context-aware Hybrid Satellite-Terrestrial Broadband Access

Erhan Ekmekcioglu, Barry Evans, Ahmet Kondo, Paul Thompson, Luc Ottavj, Fabrice Gamberini, Simon Watts

Abstract—One of the key performance targets on the European Commission’s Digital Agenda is to provide at least 30 Mbit/s broadband coverage to all European households by 2020. The deployment of existing terrestrial technologies will not be able to satisfy the requirements in the most difficult-to-serve locations, either due to a lack of coverage in areas where the revenue potential for terrestrial service providers is too low, or due to technological limitations that diminish the available throughput in rural environments. In this paper we investigate a hybrid broadband system combining satellite and terrestrial access networks. The system design and the key building blocks of the intelligent routing entities (referred to as intelligent gateways) are presented. To justify the hybrid broadband system’s performance subjectively, lab trials have been performed with an integrated multiple access network emulator and a variety of typical multimedia applications that have varying requirements. The results of the lab trials suggest that the Quality of Experience is consistently improved thanks to the utilisation of intelligent gateway devices, when compared to using a single access network at a time.

Index Terms—Hybrid Broadband Delivery, Satellite Networks, High-Throughput Networks, Intelligent Gateway

I. INTRODUCTION

End-users’ experience of broadband applications is influenced by the heterogeneity in the available access technologies. While highly populated urban areas are usually covered by a multitude of broadband technologies (e.g., DSL, fibre-optic, 3G, 4G/LTE), the prospects of content-rich services are often not available for users in the remote and rural areas that have inadequate connectivity. Emerging satellite broadband systems that provide significantly wider coverage can overcome this obstacle, where terrestrial technologies fail to appropriately cover most remote locations due to various technical reasons. In Europe, market studies [1] suggest that in many regions more than half of the homes are not likely to have access to super-fast broadband by 2020. We anticipate combining satellite broadband with the existing

terrestrial infrastructure to provide access to a significantly higher throughput. However, satellite broadband has a considerably inferior latency profile compared to terrestrial networks. Since the end-users’ Quality of Experience (QoE) has utmost importance, it is proposed to intelligently route the data traffic of different applications over the available access networks to meet the specific requirements. The proposed approach identifies the various known classes of services involved in the application data traffic, and then maps the QoE requirements on the appropriate Quality of Service levels before determining the most appropriate route for diversion. In multi-network service environments with diverse simultaneously accessed applications, it remains challenging to identify the types of services and accurately perform QoS-to-QoE mapping to maximise the overall quality of experience for all users. The goal is to fulfil the requirements of multiple applications accessed simultaneously by the household while the available access networks’ conditions are regularly monitored for traffic routing. Some applications are more bandwidth intensive than others, such as high-resolution video streaming, but less sensitive to latency, or vice versa. The streaming video bandwidth requirements can vary depending on the resolution, codec and the adaptive streaming methodology. 4K video streaming typically consumes in the range of 20~40 Mbit/s depending on the used codec, such as H.264/AVC [2] or HEVC [3]. HDTV services consume about a quarter of these figures. Online gaming typically involves significant time-sensitive data traffic (user-user, user-server, or both). Unlike streaming media, online gaming doesn’t impose strict bandwidth requirements. However, tolerance to delays and jitter is far less compared to streaming. In video streaming, one-way delay can be as much as 5s without perceivable problems apart from start-up delay. On the other hand, delays over 300ms can render the interactive gaming service non-usable [4]. Audio-video conferencing apps are tolerant to network errors to a certain extent, but delays should be well below 150ms. Furthermore, the asynchrony between the audio and video should be kept to a minimum, ideally below 80ms [5], [6], where the differences beyond 200ms are unacceptable.

The proposed system is capable of dynamically re-routing the application traffic based on application requirements and the instantaneous network conditions. This is enabled by the design and deployment of the Intelligent User Gateway (IUG) and Intelligent Network Gateway (ING) entities to direct and deliver the data packets of different services through the most suitable access network links. Statically linking the applications or devices with single access network in a hybrid broadband access context can result in subpar performance. The superior coverage and high capacity of the satellite

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broadband is seamlessly combined with the low-latency profile of the DSL networks and the ubiquity of mobile and wireless access networks.

In this paper, the satellite network design is presented. After that, the design of the intelligent gateways is presented, including the identification and decomposition of the application traffic into service classes, link estimation and intelligent routing. The design is justified with the results of the conducted subjective tests in the lab. The remainder of the paper is as follows: A brief overview of the recent hybrid network architectures is given in Section II. Section III first describes the satellite network architecture used in the proposed hybrid broadband access network, and then outlines the design principles of the proposed intelligent gateways. Section IV presents the details of the laboratory test setup consisting of the gateway prototypes and an integrated network emulator that combines three different access networks: satellite, DSL and 4G/LTE. Section IV also outlines the subjective test results from the lab trials. Finally, Section V provides the concluding remarks.

II. REVIEW OF HYBRID BROADBAND NETWORKS

Hybrid satellite and terrestrial networks employ both the satellite and terrestrial components, both of which are interconnected but operate independently, e.g., in different frequency bands, using different networks and air interfaces. The driving factors behind the hybrid service deployment include extended service coverage compared to terrestrial-only technologies, decrease in the traffic load in congested areas through load-balancing mechanisms, improvement in the operational investment cost when deploying a new service, and a broader range of service provisioning.

Previously in [7] it suggested that the satellite communication systems are superior on their own in several niche markets, like maritime and aeronautics, while they should also be integrated with terrestrial fixed and mobile networks to deliver the best service to users elsewhere. This is due to the increasing trend towards the horizontally connected (i.e., converging) systems. The integration of satellite communication with terrestrial services has been already been considered for the multimedia multicast/broadcast services owing to the bandwidth requirements of high quality and resolution video programmes [8]. While the satellite network can carry the bulk of the video traffic, particularly in advanced video formats (such as layered video, or multi-view video services) the service can be split between the concurrent satellite and terrestrial links. For instance, the basic video service can be delivered through the satellite to a geographically wider user base, and the enhancement services (e.g., higher quality layers or 2D-to-3D stereo/multi-view) can be delivered through the terrestrial links. One of the examples of the use of cooperative satellite and terrestrial networks for context-aware multimedia services was presented in [9]. The idea in this work stems from the fact that traditionally the context-aware TV services are delivered to users in a unicast fashion. This is a very costly process to be carried out by the satellite network, since satellites are intrinsically useful for

delivering services as broadcast for mass consumption. On the other hand, terrestrial networks are more capable of delivering unicast services. The authors in [9] proposed a dynamic bandwidth allocation method to utilise the satellite and terrestrial networks jointly combining unicast and broadcast methods, for serving multiple users efficiently. Since the geographical distribution of users are highly non-uniform and the accessed content are dissimilar based on multiple factors, a fixed bandwidth allocation scheme would be highly inefficient. Another prominent application of hybrid satellite-terrestrial systems is in the emergency telecommunications [10], [11]. Natural disasters can disrupt terrestrial services, whereas the satellite services are not affected as severely. Such hybrid systems typically involve setting up ad-hoc mobile mesh networks at the disaster sites for situational-awareness and fast data collection, while the GEO satellite links forming the space segment serve as the backhaul to carry the data to disaster management centres.

Software Defined Networking (SDN) that emerged in the past few years is a highly popular approach that separates the control and data planes in the network, making the connectivity of complex and heterogeneous systems simpler. SDN has also been an active research topic within the hybrid satellite and terrestrial systems. Three planes of functionalities, namely data, control, and management planes, are considered [12]. In general, the data plane consists of satellite and terrestrial switches and performs packet forwarding per flow, while the management plane governs the networking applications, service interfaces, and network status management. The control plane involves the controllers located on the earth stations, where the network intelligence is formed, including network control for routing, handover, and resource allocation. The satellite and terrestrial access network resources are federated, meaning that different resources from multiple heterogeneous domains are pooled to create one logical federation of network resources. This enables easier control and dynamic allocation of resources, which can happen among networks, such as Wide Area Network (WAN), 4G/LTE networks, and satellite access networks during service provision. In [13], the authors study an end-to-end architecture of hybrid satellite and terrestrial network under the control and user Plane (C/U) split concept, like the idea of software orchestration. One of the key aspects of the proposed architecture in [13] when compared to traditional hybrid networks is that an information-centric network (ICN) with a more flexible delivery strategy and dynamic bandwidth allocation schemes is achievable. This is a result of the deployment of a control-plane satellite communication system with the global knowledge of terminals and base stations, including the context information and user behaviours. Furthermore, the signalling overheads are reduced with the utilisation of the user-plane. As a result, the small cells eNodeB benefit from larger capacity for data transmission and reduced energy consumption. Based on the analysis of both the spectral and the energy efficiency of such hybrid networks following the optimisation of the key network parameters, it was suggested that significant energy efficiency gains can go

up to 90% with minor losses in the spectral efficiency in highly dense urban areas.

European Space Agency ESA funded several research projects to date focussing on the establishment and trials of hybrid Satellite and xDSL systems, leveraging the high throughput and fast connectivity of the respective networks. The project titled Satellite extension of xDSL copper-wire based networks [14] investigated the potential impact of hybrid systems on the value chain and in the overall telecommunications market, in terms of costs and added benefits. Technically, the question of how to reallocate the downstream xDSL bandwidth that is freed up using the satellite channel was tackled to improve the upstream performance of the involved xDSL lines. Another project titled Analysis of satellite downstream boost for xDSL networks (Sat4Net) [15] has similar scope as [14] and proposes to use the downstream satellite communications when the performance of xDSL network is not considered sufficient by the end users. Amongst the addressed challenges were interface design for satellite and ground networks, analysis and rectification of synchronisation issues between the satellite and ground (xDSL) networks. Mendhosa project (Media and entertainment delivery over hetnet with optimized satellite architecture) [16] first examined the requirements and needs of the IT & Media sectors beyond 2020 before selecting suitable integration satcom scenarios, and then assessed the benefits of innovative features on a reference SatCom architecture. In their recent study [17], authors featured the outcomes of their European Union Horizon 2020 funded 5G PPP project, titled Sat5G (Satellite and Terrestrial Network for 5G). They identified several use cases for the integration of satellite with enhanced mobile broadband (eMBB) network. These include providing satellite backhaul to individual cell towers where deploying terrestrial connections to towers is difficult, hybrid multiplex (i.e., satellite and xDSL) in homes and offices based in underserved regions, and providing enhanced broadband connectivity to moving platforms, such as aircrafts.

In this work we present a home broadband access model that can leverage the individually accessible network service resources (satellite, fixed and mobile terrestrial) in a seamless way, in order to maximise the quality of experience in relation with each application accessed simultaneously. Unlike most of prior works in this field, which study the cooperative use of terrestrial and satellite networks for specific service areas, we address the multi-service use case that is typical for home broadband access environments.

III. NETWORK DESIGN

This section first presents the design of the high-throughput satellites and then the overall hybrid network architecture with the intelligent gateways to improve the user experience.

A. A brief overview of the high-throughput satellite segment

The space segment design involves two co-located GEO satellites handling 151 user beams each and covering west and east sides of Europe. To maximise the overall throughput, the whole FSS civil Ka-band comprising the shared and exclusive bands has been allocated to the user links. The associated

system design trade-offs were presented before in [18]. A site diversity system, which is based on several optical ground stations and a highly capacitive optical fibre network, are considered to prevent the feeder link from cloud obstructions. The details on this mission can be found in [19]. The link budgets in clear weather conditions lead to a total satellite capacity of 800 Gbps and 249 Gbps on the forward and return links, respectively.

B. The hybrid network architecture

Figure 1 illustrates the overall network architecture, which comprises three broadband access segments: xDSL, cellular (4G/LTE) and satellite. Their connections are terminated at the IUG on the home user side and at the ING on the operator side. The IUG is the routing entity bringing together the satellite link and the terrestrial links. The ING that sits on the operator side manages several associated IUGs in different households and provides connection with the wider Internet. For the downstream traffic (i.e., towards the home user), an ING performs the same set of intelligent routing actions as the IUG. Both entities direct the outgoing data traffic to the most appropriate access link considering the specific requirements of each traffic flow and the status of each connection measured in real-time. The ING should be close to the Point of Presence (PoP) of the terrestrial operators (xDSL and 4G) to limit the amount of latency when the terrestrial links are active in routing. Due to the high bandwidth-delay product in the GEO satellite links, Performance Enhancement Proxies (PEPs) are used to mitigate the associated TCP PEP performance degradation. Given the number of gateways in the satellite segment, it was decided that the best compromise between performance, impact and complexity is to locate a high capacity PEP in a central point of the network near to the PoP or at the same ING. In this way, it is possible to alleviate the internal re-routing and synchronisation issues compared to a case where the PEP is located at the nominal satellite gateway and the traffic needs to be re-routed to one of the redundant gateways to avoid service interruption due to fading or failure at the nominal one.

C. The Intelligent User and Network Gateways (IUG & ING)

Randomly distributing packets among the different connections without considering the characteristic of both traffic and networks could in turn impact the users' Quality of Experience negatively. A multipath routing entity needs to be aware of the requirements of each application traffic flow and compare them with the real-time status of the available access links. The intelligent gateways consist of various modules. At the centre is the Link Selection algorithm, which selects the optimal link for a specific traffic unit. To do that, a module called Link Status Estimation evaluates the Round-Trip-Time (RTT), maximum bandwidth and packet loss rates of each access link between the IUG and the ING. The Traffic Classification module identifies the type of the traffic to take the link selection decisions and identifies the Class of Service (CoS) for QoS purposes. In the following sub-sections, more details of the mentioned intelligent gateway modules are provided.

Fig. 1. Integrated terrestrial and satellite network architecture

C.1 Multi-path routing

TCP is the primary protocol dominating today's IP traffic. This trend is driven by the service provider infrastructures, which are broadly based on this protocol set. The Internet streaming services have gradually evolved from RTP/UDP to adaptive streaming over HTTP (e.g., MPEG-DASH [20]). Multi-path TCP (MPTCP) [21] has been identified as the most suitable mechanism for our purpose. MPTCP uses multiple paths between a source and a destination simultaneously, and the interface between the network layer and the application layer remains unchanged compared to TCP. Several TCP sessions, called MPTCP sub-flows, can be established on different links to be used simultaneously whilst preserving the ordering of the packets at the far end. The implementation of the MPTCP proxies at both the IUG and ING is transparent to the integrated heterogeneous access networks. The negotiation between the IUG and ING is done using TCP options to avoid delays during payload handshakes. These TCP options need to be protected from layer-4 filtering equipment that may reside between the IUG and ING in the end-to-end path. For example, most firewalls and core network appliances modify the TCP options that they cannot interpret, which would lead to a loss of negotiation between the gateways. Thus, tunnels are utilised for the communication between the IUG and the ING to protect the encapsulated protocols including header info. In this case, a UDP encapsulation is added to ease the processing through NAT equipment.

C.2 User preferences-based stream prioritisation

Each path between the IUG and the ING should be analysed to learn the real-time status in terms of latency, bandwidth, and packet loss rate, so that the decision on link selection can be facilitated. Benefiting from the MPTCP architecture, the link estimation can be performed by regularly collecting the information from multiple TCP connections. In order to evaluate the maximum TCP bandwidth, the internal variables of the TCP control block are evaluated. These include the amount of unacknowledged data in the TCP send-buffer and the number of consecutive duplicate ACKs (DUPACKs) that have been received. When three DUPACKs are received, the

TCP host deduces that the link is congested and reduces the size of its window. At this point, the link estimation module indicates the maximum bandwidth a TCP connection can achieve. In parallel, the currently used bandwidth for each connection is estimated at every RTT interval by low-pass filtering the rate of returning ACK packets from a peer. When an ACK is received by the source, it conveys the information that a certain amount of data corresponding to a specific transmitted packet has been delivered to the destination. Averaging the delivered data count over time yields a good estimation of the bandwidth currently used by the source. When DUPACKs reach the source, they should also count toward the bandwidth estimate, and a new estimate should be computed right after their reception. Besides, the amount of sent UDP packets is also considered. Each sub-flow is estimated individually, and the sum of all estimations provides an accurate bandwidth estimate for each tunnel.

The latency and the packet loss rate are estimated through the RTT and the segment retransmission counters in the TCP kernel control blocks of each sub-flow. Another strategy is to leverage the Dynamic Link Exchange Protocol (DLEP) [22] implemented on the modems, which would feed real-time link parameters to the IUG and ING. However, this protocol is not widely adopted by manufacturers as of date.

C.3 Link selection

A novel QoS-aware link selection method called Path Selection based on Object Length (PSBOL) has been defined that considers the application traffic requirements and the real-time status of each link. At the beginning, the link selection process analyses the TCP object size, where an object is typically an Application Protocol Data Unit (APDU). The algorithm assumes that for objects that are longer than a certain threshold, the priority should be given to the high bandwidth links for reducing the overall transmission time. For short objects on the other hand, it should be preferred to select the low-latency links. The discovery of the objects' boundaries is based on an algorithm that computes the Inter-Arrival Time (IAT) between the packets. Based on this process, the size of each object is computed on the fly. Packets are initially considered a part of a small object and transmitted directly

over the lowest RTT link by default. Once the object size is found to exceed the threshold, prospective packets start to be routed through the network link with the highest available bandwidth. The algorithm compares the IAT of a packet to a threshold to decide which object that packet belongs to (i.e., the current object or a new object). This threshold is computed from the parameters locally available in either gateway devices to prevent the protocols to exchange information between the two units. This method is applicable to any TCP-based application protocol and works on unencrypted as well as encrypted TCP connections. The process takes place in both the IUG and the ING. In the ING, the process analyses the IAT for TCP packets received from Internet, and in the IUG the process analyses the IAT for TCP packets originating from the user devices. In the designed prototype, the link selection decisions for UDP traffic are based on policy-based routing, prioritising the links offering the lowest latency. This is a reasonable as UDP type traffics are associated predominantly with delay-sensitive applications. The traffic routing mechanism of the intelligent gateways is depicted in Figure 2.

Fig. 2. Intelligent gateway routing methodology

Fig. 3. Integrated network emulator test bed overview

IV. TRIALS AND RESULTS

A. Overview

A test bed has been set up for subjectively evaluating the hybrid network aggregation system using the developed intelligent gateways. The test bed comprises three access network emulators running simultaneously as well as the developed IUG and ING. In addition, an extra server (to host broadband multimedia applications) and multiple client devices (laptop, tablet) have been used during the trials. Figure 3 depicts the test bed at a high level, while Figure 4 shows a snapshot from the real setup¹ (the taller rack of servers on the right-hand side host the three network emulators).

Fig. 4. A snapshot from the integrated test-bed used in trials

Table 1. Network emulator parameter settings

Settings	D.Link BW (Mbps)	U.Link BW (Mbps)	One Way delay (ms)	Jitter (ms)	PLR
SAT-G	15	2	260	50	1.2×10^{-6}
SAT-M	12	1	300	80	1.2×10^{-5}
SAT-P	6	0.5	300	100	1.2×10^{-3}
DSL-G	8	1	20	2	1.2×10^{-6}
DSL-M	2	0.5	40	30	1.2×10^{-5}
DSL-P	0.5	0.25	100	50	1.2×10^{-3}
LTE-G	6	2	100	20	1.2×10^{-5}
LTE-M	2	1	100	50	1.2×10^{-5}
LTE-P	0.3	0.1	100	50	1.2×10^{-3}

The satellite network emulator is built on the OpenSAND platform [23], a Level-3 detailed DVB-S2 and DVB-RCS emulator. The DSL and LTE emulators are both based on the Netemu platform [24]. The emulators can be independently configured with different sets of QoS parameters through a dashboard, so that the results can be reproduced. Three different states have been defined for each emulator to apply during the experiments: Good (G), Marginal (M), and Poor (P). These states are in alignment with typical real-world

¹ A video recording, which shows examples from the trials with several use cases, can be seen here: <https://www.youtube.com/watch?v=1yT6uGfNMuM>

conditions and shown in Table 1.

The first condition (i.e., G) has been set to validate that the IUG/ING units performed as expected under realistically good operating conditions on all the transmission paths. The units were then tested to validate their performance under marginal transmission conditions (i.e., M) that are set to be at the limit of acceptable performance. The third set was to validate the performance of the units when one or more of the paths degrade beyond acceptable quality (i.e., P). Three such distinct sets of conditions have been established for all the links to make sure that the tests are repeatable equally for all the subjects attending the trials.

B. Subjective tests

Four applications have been used to measure the QoE in the presence of IUG and ING. These are: video streaming in high definition, browsing, video chat, and gaming. Video streaming and browsing include TCP data traffic while the video chat and gaming applications include UDP traffic too, as they are relatively more sensitive to latency. The tests have been performed in an isolated network to prevent the influence of any Internet-associated issues that are beyond our control. Thus, all applications are hosted by the application server integrated to the test-bed, as shown in Figure 3. For the video streaming application, several test videos were generated at an average bitrate of 8 Mbit/s using H.264/AVC and audio encoded at 0.5 Mbit/s and kept in an Apache web server. For browsing, ten different web sites have been pre-copied (all content including the content accessed through the links on the landing page and others) into the same Apache web server using the website copier HTTrack [25]. The integrated network emulator connects the client devices used by the subjects to the application server. The copied sites have been bookmarked on the Internet browser in the client devices and all cookies and cache are automatically deleted after each test. Cookies and cache are cleared deliberately to prevent the browser to use them next time, which will otherwise impact the web browsing experience despite the changes in the network condition. The ten websites used in the lab trials were selected amongst several open blogs created by high end web tools and that use the secure sockets layer for communication (i.e., secure HTTP or HTTPS). This was done deliberately, since the proportion of the HTTPS traffic is growing rapidly, and this is seen in many popular websites [26]. Amongst the interest categories are travel, culinary, photography, lifestyle, fashion and video games. Attention was paid to the fact that all blog content comprises high definition and/or medium-scale image content on most of its pages and in some cases videos as well. Note that those videos are not copied by default using the HTTrack website copier. Therefore, those videos in the selected websites were manually downloaded into the web server, recompressed at fixed bit-rate without compromising visual quality and linked to the anticipated webpage, such as the video streaming starts (default HTTP streaming) as soon as the player is clicked by the user. We wanted to make sure that the users participating in the trials and testing the web

browsing function at different times can access various content of potential interest without having to stick to the same page(s), which would otherwise create an artificial experience. Similarly, to reflect a real-life usage scenario, we ensured that nearly all accessible pages through clicking on different links include multimedia content (i.e., image, video or both) in addition to text. For video chat, the application called Ekiga [27] was installed on the client devices and the host application server. In the video chat scenario, subjects talked to the test coordinator sitting in front of the host server, which is equipped with a webcam too. To facilitate meaningful talks between the subject and the test coordinator, some brief conversational scenarios have been created according to the ITU-T recommendation P.920 [28]. For gaming, the Counter Strike game server (a First-Person-Shooter type game) has been installed on the host server PC and the associated game application has been installed on the client devices. In this game, the main character navigates through an artificial battle platform with the aim of targeting and shooting the enemies using the mouse and the keyboard buttons. Figure 5 shows a snapshot from the game. The frame interpolation feature, which mitigates the impact of heterogeneous delay differences across network gamers in real settings, has been disabled through the source engine to reflect the influence of the network conditions and the intelligent gateway actions on the game QoE.

Fig. 5. Sample screenshot from the online gaming test scenario

The subjective tests were conducted in two groups. The first group involves a single broadband application accessed at a time by a subject through test bed, whereas the second group involves two applications accessed simultaneously by separate subjects. The IUG and ING are expected to analyse the applications traffics, measure the link conditions, and route them through the most suitable link based on the QoE requirements. In order to measure the gain obtained by the intelligent gateways, each test application was also accessed through the individual access network emulators with their specific settings (i.e., without the intelligent gateways used). The aim is to measure the minimum and the maximum achieved levels of the QoE for each application. Hence, it is possible to judge whether deploying the IUG and ING leads to an improvement in the QoE or not. Table 2 depicts the test categories and the attributes.

Table 2. Subjective test categories and the associated attributes

Test category	Attributes
Experiment I, Part 1	Single subject, single application over a single network (IxG inactive)
Experiment I, Part 2	Single subject, single application over a combination of three networks (IxG active)
Experiment II, Part 1	Two subjects, two applications over a single network (IxG inactive)
Experiment II, Part 2	Two subjects, two applications over a combination of three networks (IxG active)

The test operator was in a server room, changing the network emulator settings between each test, where each test is an instance of an application. The test operator also helps during the video conferencing test by talking to the subject who sits in the subjective test room and uses the test client. The subject is accompanied by another person in the same room, who introduces the subject to the test, instructs how to use the score sheet and tells when he/she should start with the next test.

Twenty-four non-expert users from a diverse age range and Internet usage background participated in the subjective tests. None of the users had prior acquaintance with the specific testing methodologies employed, or how the subjective tests were designed. The number of users, which is in line with the suggested testing conditions in several ITU-T recommendations (such as BT.500-11, P.910, P.911, P.913, P.920), was suitable to generate statistically relevant results. These recommendations assume controlled testing conditions and set best effort rules to generate unbiased results. The application usage experience statistics revealed that web browsing is the most widely used application by all subjects, followed by video streaming, video conferencing, and finally online gaming.

C. Test results

Figure 6 depicts the Mean Opinion Score (MOS) results of Experiment I (parts 1 & 2) and Figure 7 shows the MOS results of Experiment II (parts 1 & 2). Considering the results from Figure 6 and Figure 7, the following key observations are noted:

- In the absence of IUG and ING, where the applications were routed individually on different network emulators, it was seen that the user experience changes on a sufficiently large scale. Therefore, the positive gain of deploying the IUG and ING in the system was noticeable.
- With IUG and ING in place, the variations in the MOS across different network combinations were limited. On average, the MOS was close to the upper limit, where the upper limit denotes the maximum achieved MOS for that particular application when the best network choice was made. This shows that the application traffic routing is done correctly by the installed intelligent gateways.

- When more than one applications were used (Experiment II), the results indicated that similar to Experiment I, the MOS of both applications were consistently close to their upper limits. This shows that the intelligent gateways can also correctly classify different traffics and treat them differentially.
- While the HD video streaming task was loaded on the satellite network, the web http traffic was mostly routed through the DSL due to the low latency requirement. Nevertheless, when web pages with large pictorial or video content were loaded, the intelligent gateway adaptively reacted to it by routing the traffic to the satellite network for faster download times.

After further analysis, the following observations are made:

C.1 HD multimedia streaming

- Bandwidth is the most crucial QoS criterion for the tested video streaming application, where the users' QoE varies significantly over different channel conditions.
- Despite its significantly inferior latency profile compared to the DSL network, the high throughput satellite link improves the video streaming experience remarkably, while the DSL channel can barely provide acceptable levels of service.
- The impact of the latency at the beginning of video streaming in the satellite link is rather negligible.

C.2 Web browsing

- The QoE in the case of web browsing is not only dependant on the network latency, or only on the throughput. It is affected by both, depending on the web browsing activity (e.g., content).
- Page response time is an important factor. This is accommodated by the low-delay terrestrial link (i.e., DSL link) chosen at the beginning of each sub-flow.
- Depending on the size of the page (e.g., number and size of the included multimedia files), the traffic was dynamically routed over the satellite link to facilitate fast content download.
- The best QoE was observed when the user had a decent DSL connection with sufficiently high throughput. When this is not the case, the bulk of the page content can be retrieved through the satellite link, which still leads to comparable QoE. This can be observed in Figure 6(f), especially when the DSL emulator is set to 'Poor' (P).

C.3 Video conferencing

- It was observed that the QoE was high as long as the network provides sufficient bandwidth for the transport of the video and audio streams.
- Even in the satellite link with inferior latency performance, the QoE was sufficiently high. The most notable issue with the video conferencing application was the degrading audio and video quality, which was associated with the channel throughput.

Fig. 6. MOS results for Experiment I. (a) ~ (d) for Part 1 and (e) ~ (h) for Part 2. (a) & (e) for HD multimedia streaming, (b) & (f) for web browsing, (c) & (g) for video conferencing, (d) & (h) for online gaming. The emulator configurations for Part 2 are presented in the format of [Sat condition, DSL condition, LTE condition] (e.g., MGP, PGG, MGM...). On the graphs (e) ~ (h), the dashed lines represent the achieved levels in Part 1. These are displayed to make an easy comparison between the experiences with and w/o the use of IUG & ING.

Fig. 7. MOS results for Experiment II. (a) ~ (d) for Part 1 and (e) ~ (h) for Part 2. (a) & (e) for [HD multimedia streaming + video conferencing], (b) & (f) for [HD multimedia streaming + online gaming], (c) & (g) for [HD multimedia streaming + web browsing], (d) & (h) for [online gaming + web browsing]. On all the graphs, the horizontal lines depict the maximum and minimum observed MOS values for each application from Experiment I (i.e., upper and lower limits). These are displayed for comparison purposes.

- The intelligent gateways were able to classify the type of the traffic and video conferencing data is regarded as latency-sensitive.

C.4 Online gaming

- The gaming application is latency-sensitive but doesn't demand as much bandwidth as the video conferencing application.
- The impact of the latency on the QoE is more visible especially when the traffic is carried over the satellite link (note that in Figure 6 (h), the quality is comparable between the cases where the DSL network is in 'Poor' condition and the Satellite network is in 'Good' condition).
- The QoE is broadly in the "Good" or "Excellent" ranges (i.e., above 60/100) in the existence of the intelligent gateways.

Overall, the test results have demonstrated that in the controlled lab environment the utilization of the IUG and ING in addition to multiple access network connections provides significantly improved QoE in several everyday applications.

V. CONCLUSION

In this work a hybrid broadband access architecture (satellite and terrestrial) has been designed and tested with intelligent user and network gateways, which facilitate the routing of the application traffic over the most appropriate of the available access networks. The proposed system can classify the data traffic per flow and is able to measure the performance of the available links in real-time. As a result, it can take the most appropriate routing decision for each application to maximise the resulting QoE per application. The subjective tests conducted in a comprehensive test bed showed that the proposed system improves the QoE for a variety of commonly used multimedia-based applications.

It is envisaged that the proposed intelligent gateways will especially be useful to serve the less well-served geographical locations by efficiently integrating the satellite broadband and the terrestrial broadband systems. The aim is not to just simply maximise the throughput via network aggregation, but to optimise the resource usage by maximising the QoE associated with the broadband applications accessed.

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