Satellite Support for Enhanced Mobile Broadband Content Delivery in 5G

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Abstract—**Satellite communication has recently been included as one of the enabling technologies for 5G backhauling, in particular for the delivery of bandwidth-demanding enhanced mobile broadband (eMBB) application data in 5G. In this paper we introduce a 5G-oriented network architecture empowered by satellite communications for supporting emerging mobile video delivery, which is investigated in the EU 5GPPP Phase 2 SAT5G Project. Two complementary use cases are introduced, including (1) the use of satellite links to support offline multicasting and caching of popular video content at 5G mobile edge, and (2) real-time prefetching of DASH (Dynamic Adaptive Streaming over HTTP) video segments by 5G mobile edge through satellite links. In both cases, the objective is to localize content objects close to consumers in order to achieve assured Quality of Experiences (QoE) in 5G content applications. In the latter case, in order to circumvent the large end-to-end propagation delay of satellite links, testbed based experiments have been carried out to identify specific prefetching policies to be enforced by the Multi-access computing server (MEC) for minimizing user perceived disruption during content consumption sessions.**

I. Introduction

In the emerging 5G era, technologies for supporting enhanced Mobile Broadband (eMBB) are being investigated for improving content delivery capabilities. Specific content delivery services (e.g. 4K/8K video and also immersive virtual and augmented reality applications) can be offered to mobile users while on the go. Mobile users are now accustomed to a certain quality of experience (QoE) in these applications, and their expectations have been growing concerning overall video quality. Tablets, smartphones, and other IP-connected devices are nowadays able to support high video bitrates, and thus the bottleneck does not reside in the device side, but in the network ability to deliver the content. In this context, one major mission of technology development for 5G eMBB is to assure user QoE in dynamic network conditions. As far as video applications are concerned, we envisage the following key QoE metrics:

- **Video quality**: Adaptive bitrate technologies have been crucial with allowing mobile users to access video content by automatically adapting quality to the dynamic bandwidth availability. In the 5G era, the service level agreement will become more stringent on the video quality to be delivered, for instance guaranteeing 4K video quality to premium users.
- **Video disruption statistics**: This refers to the undesired events when stalling takes place during video playback, which can severely affect user QoE.
- **Start-up delay**: This indicates the duration between when a user makes the content request and the start time of the video play back.
- **Latency in live streaming**: This is the time gap between the true progress of the event being streamed and what is being played back at the user device side.

In order to comprehensively support QoE in 5G content delivery, network resources need to be carefully provisioned according to specific application requirements and scenarios. Satellite communication can play its distinct role in contributing to 5G video delivery thanks to its high bandwidth capacity and the efficiency of supporting large-scale multicast. For instance, popular video content can be proactively preloaded and cached a priori at the 5G mobile edge where there expect to be a large crowed of local consumers. Since such an operation is offline and hence is not delay sensitive, satellite based multicast is an ideal solution to deliver popular content from the remote source to individual local caching points close to local consumers before they start to make request. On the other hand, it is also a natural question whether it is possible at all to direct stream high-quality video content over satellite links? If the traditional end-to-end solution is not able to fulfil such a task due to the long latency, how can necessary network edge intelligence circumvent such a situation? This paper mainly addresses the scenarios being investigated by the EU 5GPPP-2 SAT5G Project [2], for leveraging satellite communications to support QoE-assured content distribution in 5G.

In this paper we mainly introduce the SAT5G use cases where satellite links are essential network resources to enable backhauling and traffic offloading in 5G content delivery, in particular for Video-on-Demand (VoD) scenario. In this case it is envisaged that necessary content caching resources can be maintained at the 5G mobile edges for storing (popular) content items which are expected to be consumed by a large

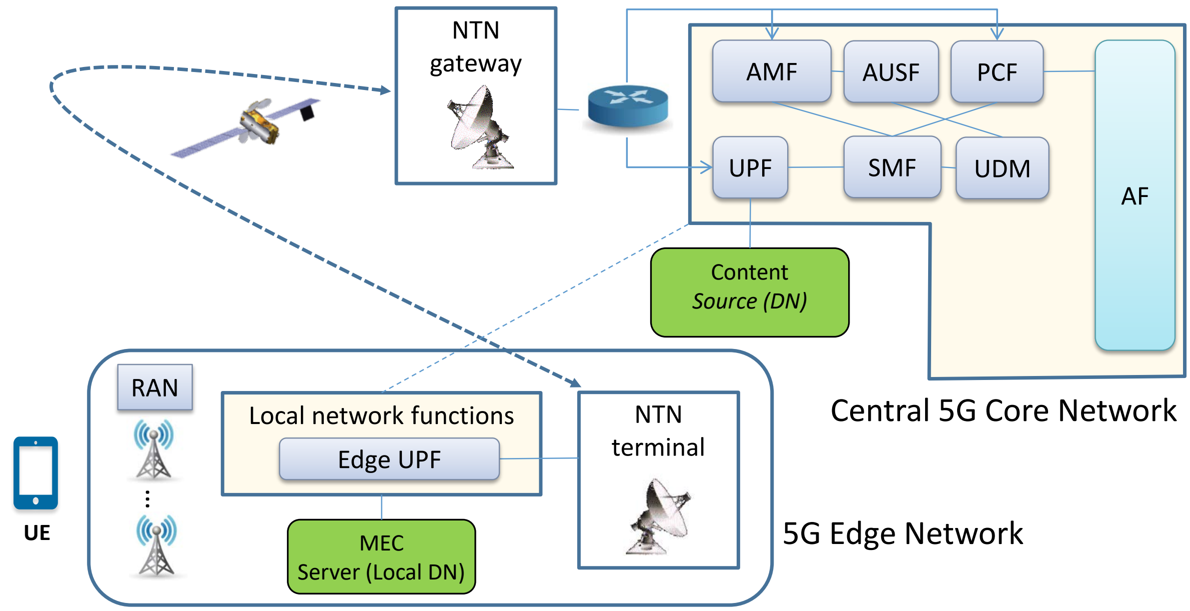

Fig. 1. Edge content delivery and offloading in 5G supported by satellite links

number of local mobile users. In this case, satellite communications can leverage its broadcasting/multicasting capability to pre-populate video content from the original content source to multiple network locations (e.g. point of presence PoP) where local caching resources are attached. As shown in Figure 1 which shows the satellite-involved 5G architecture based on 3GPP [1], all the control-plane virtual network functions (VNF), including AMF (Access and Mobility Function), AUSF (Authentication Server Function), SMF (Session Management Function), PCF (Policy Control Function), UDM (User Data Management) and AF (Application Function) are located at the central 5G core, together with the core network user plane function (UPF) that offers the content delivery service originated from the remote video source in the external data network (DN). The central 5G core and individual mobile edge network at different locations are connected through satellite links. To realise this, a non-terrestrial network (NTN) gateway is deployed at the 5G core side, while an NTN terminal is attached at the mobile edge side, and together with the satellite itself form the satellite backhaul infrastructure. Based on various context information including the local learning and prediction outcome of content popularity, AF is able to make necessary decisions on the corresponding content handling operations to be applied, including multicasting, caching, prefetching at the 5G mobile edge. For some of these operations, the satellite links can be activated for offloading content traffic from the terrestrial network, even with the multicast capability. Once the content has been available at the local mobile cache, known as Mobile Edge Computing (MEC [5]) server, then the incoming content requests can be locally re-directed through the edge UPF to the MEC server rather than towards the original content source. A key technical issue in this use case is the knowledge about the content popularity at different regions so that the multicast delivery operation of content can be specifically triggered.

In addition to such proactive multicasting and caching of popular content at the mobile edge which is suitable for assuring user QoE for popular content, we additionally analyse the feasibility of on-demand video content segment prefetching through satellite links upon user requests. The typical application scenario is Dynamic Adaptive Streaming over HTTP (DASH) which has been widely used in todays video services like YouTube. In DASH, the whole video content is chunked into multiple fixed-length segments which can be independently requested by clients. In order to assure user experiences in terms of disruption freedom, each DASH segment has multiple bitrate versions, each representing a specific video quality. Such a feature enables video quality adaptation on the client side according to the dynamic resource availability of a session. Concerning the mission of using satellite links to stream high quality DASH video content, e.g. at the 4K level, a distinct challenge is the long propagation latency which may severely affect the actual data throughput performance of TCP according to the traditional approach of end-to-end delivery. To address such an issue, we adopt the context-aware DASH segment prefetching technique at the 5G mobile edge in our previous work [7] [6], and evaluate how such a solution can be applied in the satellite environment. Such an approach with necessary network edge intelligence is complementary to the previous scenario that is more suitable for popular content, whereas the delivery of other video content can be still optimised in terms of user QoE during run-time.

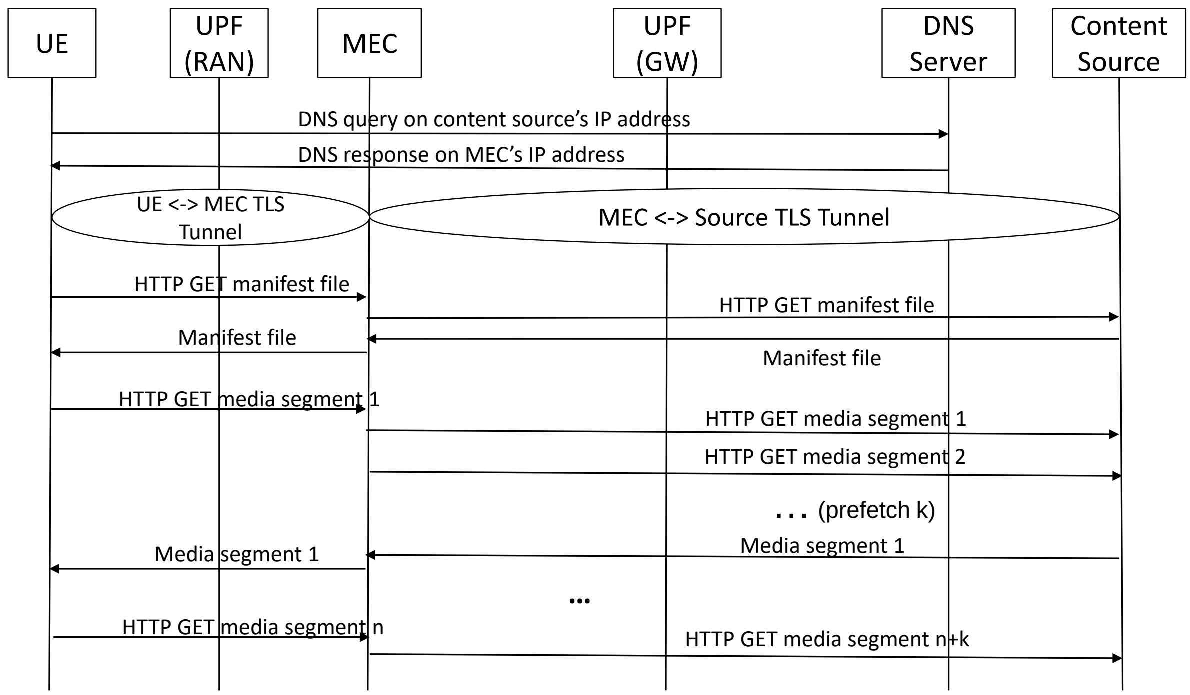

Fig. 2. Signaling sequence diagram for MEC prefetching

II. Offline multicast and caching through satellite links

One distinct benefit of the satellite network in content delivery is its capability of multicasting content towards different network locations. This is particularly useful for offline delivery of popular content objects to MEC servers at different locations where there expects to be a large number of content consumers with common interests. Since these content objects are cached locally a priori, future incoming requests can be directly served by the local MEC server but without necessarily being resolved to the original content source. From user point of view, such an operation is able to enhance quality of experiences in terms of both reduced start-up latency and video quality thanks to the boosted TCP throughput due to shortened delay.

Now we elaborate how such operation can be executed by a 5G network platform with embedded satellite components. As shown in Figure 1, the entire 5G network architecture is split into two parts: the central 5G core network and 5G network that can be distributed at different locations. The satellite links are responsible for connecting the central 5G core to individual network edges, typically via the NTN gateway and the terminal on the two sides. Concerning different business models there can be specific scenarios to enabling satellite-assisted content delivery. Specifically, if the underlying 5G operator is also the content provider (e.g. British Telecom who also offers BT TV service), then the task of content management is simply managed by one single stakeholder. In this case, the Application Function is responsible for generating network intelligence, including necessary learning and prediction operations to predict content popularity at different locations. Based on such knowledge, locally popular content can be proactively pushed down to individual MEC servers at 5G edges via multicast-enabled satellite links. Once the content has become available at the local MEC servers, the corresponding content resolution should also make sure the future incoming request will also be redirected to the MEC server rather than being delivered to the original content source. To do this, the AF will also interact the DNS system to make sure the requests to the cached items are always forwarded to the local MEC server.

Another more complex scenario is that content management is done by external content providers or CDN operators who may want to collaborate with the underlying 5G network operator. In this scenario the content management system operated by the third party should synchronise with the AF in terms of caching decisions. Specifically, the necessary content intelligence (e.g. prediction of content popularity at different locations and also the corresponding caching decisions) is produced by the third-party content provider.

III. Online DASH segment prefetching through satellite links

A. Scheme description

In addition to the offline multicasting of popular content to the mobile edge for local access, we also investigate how satellite links can be directly involved in the real-time delivery of video content in 5G environments. It is apparent that the long propagation delay of satellite links is a major issue that can affect the end-to-end performance of DASH/HLS video streaming based on TCP. According to the recent studies even based on the terrestrial scenario [7] [4], TCP throughput performance suffers substantially across any end-to-end path containing heterogeneous path segments with substantially different bandwidth-delay product (BDP). Specifically, in a mobile environment, the radio access network (RAN) part typically has a low BDP value as compared to the back-haul/Internet part with long delay (up to 350ms for terrestrial networks) and a fat data pipe. It can be easily inferred that the additional delay introduced by satellite links make the situation more challenging, and indeed the poor end-to-end performance in DASH video delivery can be observed from Figures 4 and 5 in the next section.

In order to circumvent such a situation, the authors of [7] [6] proposed a context-aware DASH video segment prefetching technique in order to substantially boost the end-to-end TCP throughput performance in 4G LTE-A environments. The key idea is to leverage a multi-access edge computing (MEC) server that is responsible to intelligently prefetch on-demand an optimal number of DASH video segments from the original content source and make them locally available to the consumers. Specifically, the scheme leverage on the fat pipe of the backhaul and Internet path to establish additional TCP connections in a controlled manner to prefetch future segments ahead of user requests during a real-time video session. Such a solution does not require the pre-caching of video content at the mobile edge a priori, which makes it an ideal solution even for non-popular content objects. According to the experiment study based on the terrestrial networks, the proposed approach is able to achieve QoE-assured 4K video delivery across the entire Internet provided that there are adequate radio resources on the RAN side. In this section we describe how this scheme can be extended to the 5G network environment with satellite links being involved as the backhaul.

To start with, the content provider, which can be either any third party or the MNO itself (in case the MNO also takes the role of content provider) should define specific prefetching policies through the Application Function (AF) according to the 5G network architecture. For instance, the most important configuration policy is how many DASH video segments should be prefetched for each content session through the satellite backhaul? Such policies will be actually enforced at the MEC server which is responsible for storing the prefetched or cached video content as the local source. In addition, the mechanism should be also developed to redirect the user content requests to the local MEC rather than the remote content source. A common approach is through the DNS system where AF can reconfigure the local DNS server to point to the IP address of the local MEC which is ready to launch the prefetching operation upon any incoming requests on the content URL. Figure 2 illustrates the sequence diagram on the actual operations. If the user equipment (UE) has received the returned DNS response that points to the local MEC server, then it will establish a secured TLS tunnel with the MEC server to start content delivery. In case the content has not yet been locally cached, the MEC server will also establish

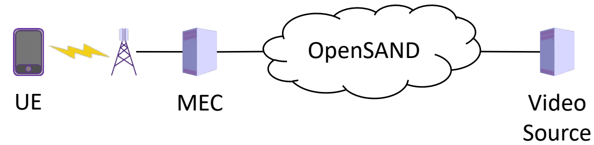

Fig. 3. Experiment setup

a secured TLS connection with the remote content source for prefetching purpose. In the context of the DASH applications, the UE will first request to the MEC server the manifest file known as MPD (media presentation description). The MEC server will on-demand fetch the MDP from the source and return it back to the UE. Upon receiving the first request on the DASH video, the MEC server will start to activate the prefetching operation which makes its segment downloading progress constantly ahead of the UE request.

B. Performance analysis

Now we systematically analyse the performance of the prefetching operation through satellite links in an emulated 5G environment. For simplicity the radio access network is based on WiFi while the satellite link is emulated with the OPENSAND software tool [3]. The setup topology of our experiment is illustrated in Figure 3. We follow the same methodology as the previous work [7] where the given video bitrate is fixed at 10Mbps which is adequate for supporting 4K video streaming based on HEVC. The duration of the video clip is 2 minutes and the DASH segment length is set to 2 seconds. We deliberatively disable the DASH video adaptation function below 4K video quality, and the reason for this to investigate user QoE performances under a given targeted video service product. In this context, the actual user QoE metrics include the following: (1) the actual segment downloading throughput, (2) video start-up delay and (3) video playback disruption statistics such as frequency/duration of the picture stalling events.

The performance comparison is carried out between the following three scenarios based on the common experiment setting:

- No prefetching: i.e. to simply use the satellite link as the 5G backhaul to directly stream DASH video at the fixed bitrate of 10Mbps.
- 3-ahead prefetching: i.e. the MEC server tries to keep a constant pace of 3 segments to be prefetched ahead of incoming UE requests.
- 6-ahead prefetching: i.e. the MEC server tries to keep a constant pace of 6 segments to be prefetched ahead of incoming UE requests.

Figure 4 shows the DASH downloading throughput comparison across the three schemes. It is easy to observe that the traditional end-to-end scheme severely suffers from poor downloading throughput which is constantly and significantly below the video bitrate of 10Mbps. As a result, the user

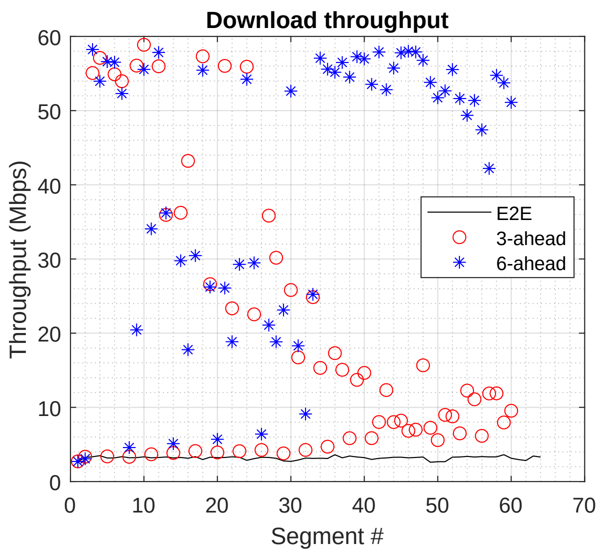

Fig. 4. Segment downloading performance comparison

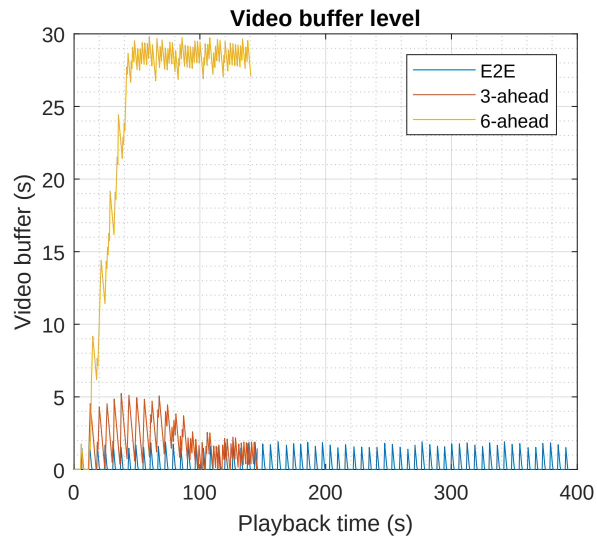

Fig. 5. Video buffer performance comparison

perceived QoE in terms of video buffer conditions is rather poor, as can be seen from Figure 5. Here it observed that the actual UE buffer status is constantly very low and frequently experience stalling (when the buffer level becomes 0). From user point of view, even though the video quality is kept at 4K level, due to frequent picture freezing it takes nearly 400 seconds to play back the video clip with total duration of 2 minutes (i.e. 120 seconds). Effectively, this means the direct end-to-end video streaming at the 4K quality level cannot be achieved if satellite link is involved as the backhaul.

Now we focus on the prefetching-based approach, and apparently one of the interesting issues is, what is the minimum number of segments that needs to be prefetched at the mobile network edge that is adequate for supporting disruption-free playback at the UE side without sacrificing the 4K video quality? For this purpose, we tested two different scenarios, namely 3-ahead and 6-ahead. From Figure 4 we can see that both approaches are able to substantially boost the actual segment downloading throughput which is statistically above the required video bitrate of 10Mbps. Nevertheless, 3-ahead (i.e. prefetching 3 segment ahead of UE requests) has higher chance to have the actual throughput get very close down to 10Mbps, making the situation potentially risky in terms of user QoE. This can be reflected in Figure 5 where the video buffer can still get starving during the playback. In comparison, 6-ahead is able to further improve the performance by being more aggressive in prefetching segments. As can be seen from Figure 4 and 5, the chance of getting the actual downloading throughput is much lower compared to the 3-ahead scheme, and as a result it takes a short period of time for the video buffer to reach its maximum level (30 seconds), meaning that during this period of time there is no disruption when playing back the video.

Finally, Table I shows the key performance summary across the schemes under investigation. As can be seen, the start-up delay is very close with each other. This is because even prefetching needs to be triggered by the initial user request, and intuitively the very first video segment cannot be prefetched in any case. However, both of the two prefetching schemes are able to substantially reduce the rebuffering duration compared with the traditional end-to-end approach. This table also quantify the performance improvement from 6-ahead with further reduced rebuffering duration (down to 8.7 seconds from 13.8 seconds). The reason behind can be explained by the percentage of successfully prefetched segments at the mobile edge which is ahead of the actual incoming request for that segment. With 3-ahead policy, only 15% of the segments can be made ready at the mobile edge as compared to 69.6% with 6-ahead.

TABLE I
PERFORMANCE SUMMARY

	Startup Delay (s)	Rebuffering Duration	Prefetched segments in time
E2E	6.2s	262s	N/A
3-ahead	6.0s	13.8s	15%
6-ahead	6.1s	8.7s	69.6%

IV. HIGHLIGHTS OF ADDITIONAL CHALLENGES

Apart from the technical challenges for supporting user QoE in 5G-based content services, we also envisage the following issues in utilising satellite communications in 5G networking. First of all, the underlying business value chain for involving satellite network operator in the 5G-based content ecosystem needs to be defined. Further business modelling is required to quantify the CAPEX/OPEX involved in the satellite operations for supporting 5G content delivery, together with the expected revenues made by specific stakeholders. On the technical side, while the SAT5G Project mainly targets the backhauling service from the original content source to the mobile edge where either content cache or media gateway is presented for further delivery to end users, its interworking with the last-mile radio access network (RAN) needs to be optimised for the sake of comprehensive user QoE assurance (guaranteed video quality, disruption-avoidance, minimised start-up delay and live streaming latency). In addition, in the scenario where satellite links provide an alternative communication channel for offloading content traffic from the fixed network infrastructure, appropriate decision-making process needs to be developed in order to best utilise network resources on both sides. Concerning security requirements, the multilayer streams used for multicast-assisted ABR (adaptive bitrate) formats are protected by Digital Rights Management (DRM) as opposed to Conditional Access Scrambling (CAS), which is traditionally used for satellite distribution. The solution has to be compliant with all DRM and transparent to the encryption.

V. Conclusion

In this paper we introduced an architecture framework for supporting satellite communications to take role of backhauling in 5G networks. The main use case focus is on the delivery of eMBB based video content to 5G users via satellite links. This includes the scenarios of both offline multicasting of popular content to be cached at the local MEC server and real-time prefetching DASH video segments for assuring user experiences. The paper specifically describes the extension of traditional video segment prefetching technique to be used in the satellite network environment, where the direct end-to-end streaming of 4K quality video content is not possible through satellite links with excessive delay. Through real testbed experiments, we evaluate the efficiency of different segment prefetching policies that can be potentially applied in the satellite environment, which are able to substantially improve user QoE compared to the legacy scheme.

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