

Efficient Media Streaming with Collaborative Terminals for the Smart City Environment

Jordi Mongay Batalla, Piotr Krawiec, Constandinos X. Mavromoustakis, George Mastorakis, Naveen Chilamkurti, Daniel Négru, Joachim Bruneau-Queyreix, and Eugen Borcoci

The authors introduce the architectural modules required for collaboration streaming inside the radio access network and end user's device, and they propose enhancements in HTTP-compliant adaptive streaming protocols in order to become suitable in a multipath collaborative scenario.

ABSTRACT

Among multiple services delivered over future mobile networks, the most demanding (from the required bandwidth point of view) are related to media streaming, which is a key component in smart applications (entertainment, tourism, surveillance, etc.). Such applications have to exploit a considerable amount of data, which is difficult to achieve especially in dense urban environments. In this context, the article presents a new solution for HTTP-compliant adaptive media streaming applicable to future 5G mobile networks, aimed at increasing bandwidth availability through the use of multiple radio access technologies and direct connections between devices if they are in proximity of each other. The proposed solution considers a scenario in which a high-quality media stream is received by multipath transmission through the radio access network. Collaboration of neighboring devices is exploited by using direct device-to-device links. Thus, proxy nodes can be inserted between a given media receiver and an access network. Toward ensuring optimized resource allocation at both levels, base station-to-device and device-to-device, this article introduces the architectural modules required for collaboration streaming inside the radio access network and end user's device, and proposes enhancements in HTTP-compliant adaptive streaming protocols in order to become suitable for a multipath collaborative scenario.

INTRODUCTION

Multimedia emerging applications including advanced video definition (4K, 8K) together with other features such as augmented reality, 3D, or multi-angle vision will flood mobile networks in the near future. Multimedia delivery in a large metropolitan area will require wireless network infrastructure to handle much higher traffic volume than today. These requirements are targeted by the novel fifth generation (5G) mobile network. The 5G design aims to enhance the system capacity in urban areas, mainly to be achieved by:

- Higher spectral efficiency thanks to massive multiple-input multiple-output (MIMO) techniques
- Infrastructure densification by widespread

deployment of small (micro/pico/femto) cells, jointly with support of heterogeneous radio access technologies (RATs)

- Usage of additional spectrum, particularly from the millimeter-wave region, which may provide high bandwidth, but with relatively short-range coverage due to line of sight propagation with minimal refraction

In addition to the capacity increase, the radio access network (RAN) in urban areas — characterized by high density, in terms of population, buildings, and traffic demand — should introduce new mechanisms to efficiently manage the resources. The bandwidth available for users can vary substantially even in neighboring locations. On the other hand, the urban environment increases the probability of finding networking devices, which could act as intermediate nodes between media consumer and media source.

Collaboration is commonly considered as a way to improve the efficiency of resource usage in scenarios with physically dense networks, such as smart cities. Some research studies have proposed a collaborative framework for reducing congestion at the network backhaul by caching popular media content at base stations or mobile devices [1, 2]. The advantage of such solutions is their simplicity; however, they do not solve the problem of reduced bandwidth access for a single end user. Another scope refers to improvement of streaming capacity thanks to aggregation of downlink rates available for collaborating terminals. Many publications propose overlay solutions installed on top of the network and, possibly, profiting from facilities (e.g., server capacity) of the network. These solutions suffer high response delays and inefficiency in resource usage. Moreover, they are constrained by a supplementary service agreement in addition to the one with the mobile operator. Examples of such solutions are [3–6]. Proposals [3, 4] are solutions for HTTP direct download, which is not compliant with current network conditions where adaptive streaming protocol is required. Only [5, 6] present overlay solutions with adaptive streaming. To the best of our knowledge, only Syrivelis *et al.* proposed a network-native solution for collaborative streaming by the use of software defined networking [7]; however, it does not consider adaptive streaming,

Jordi Mongay Batalla and Piotr Krawiec are with the National Institute of Telecommunications and Warsaw University of Technology; Constandinos X. Mavromoustakis is with the University of Nicosia; George Mastorakis is with the Technological Educational Institute of Crete; Naveen Chilamkurti is with La Trobe University – Melbourne; Daniel Négru and Joachim Bruneau-Queyreix are with the University of Bordeaux; Eugen Borcoci is with University Politehnica of Bucharest.

Digital Object Identifier:
10.1109/MCOM.2017.1600225CM

which excludes the solution from implementation in real networks.

The solution presented in this article proposes a collaborative framework managed directly by the RAN, which is responsible for governing uplink/downlink access, but also controls the state of the device-to-device (D2D) links. Our solution merges network-assisted device cooperation with modern adaptive streaming functionality to ensure optimal radio resource allocation jointly with the highest video quality perceived by users.

The rest of the article is organized as follows. The next section presents the architecture for collaborative streaming management in dense heterogeneous networks (e.g., cities) specifying the proposed modules and entities. Then we show the enhancements in the end devices required for making collaborative media streaming feasible and discuss the resource allocation in the system. After that we present the solution for adaptive streaming in the multipath collaborative scenario. Results of the implemented solution in contrast to other uni- and multipath proposals are included. At last, the final section concludes the article.

ACCESS NETWORK ARCHITECTURE FOR COLLABORATIVE MEDIA STREAMING

Highly dense heterogeneous networks (HetNets) may increase the efficiency of radio spectrum usage by dividing the space into micro- and picocells. Multiple antennas and multiple RATs may increase the capacity of a RAN only if the system is capable of locating each mobile device and executing appropriate algorithms to automate the cooperation procedures. Such functionalities are generally located in the remote radio head (RRH) within micro/picocells. On the other hand, the use of cloud methods for control and management of the radio resources may greatly help with the introduction of such complex algorithms [8]. These cloud facilities are located in the baseband units (BBUs). BBUs are responsible for the signal processing and layer 2/layer 3 functions, detaching these functions from the conventional base stations and moving them to a centralized location. The distributed conventional base stations now become simple RRH modules that perform conversion between digital baseband signals and analog signals transmitted/received by antennas.

In centralized RAN (C-RAN) [8], the BBUs run as a virtualized pool of processing resources in a dedicated data center or using cloud services, and can be shared between different RRHs. In this way, the network operators can reduce energy consumption in the mobile infrastructure, decrease both deployment and operational costs of BBU, and also facilitate network upgrades and future migrations to new solutions. Furthermore, emerging mobile edge computing [9] servers deployed on RAN premises can offer spare cloud computing capabilities available at the RAN to authorized third parties, using open interfaces. It allows additional functionalities to be launched at the RAN, such as caching and transcoding in the case of media streaming.

We propose to increase cooperation of technologies in HetNets for ensuring high-quality multimedia streaming anywhere in the city. In a basic scenario an end user intends to download

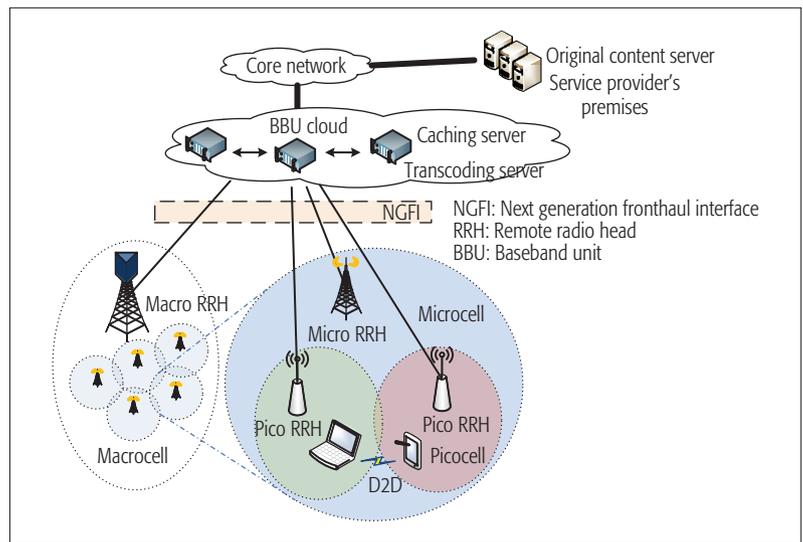


Figure 1. C-RAN architecture.

a high bandwidth stream (in general, video) by using an HTTP adaptive connection (Fig. 1). To this aim, a collaborating relay device (if possible) may download portions of the media, exploiting the downlink bandwidth available to it; next, it retransmits the downloaded media to the receiver (end user) via a direct D2D link. An efficient collaborative streaming should involve different RATs with coordinated spectrum usage (e.g., LTE for downloading media from the network, and WiFi, Bluetooth, or LTE-Direct to transfer the media directly between user devices) as well as make use of current adaptive streaming protocols for adapting the media bit rate to the overall download rate.

A centralized BBU architecture is more consistent with collaborative media streaming than edge computing, given the availability at the BBU level of device contextual information that is important for making appropriate collaboration decisions. Although various schemes of splitting the baseband functionality between BBU and RRH have been investigated [10], depending on fronthaul capacity and delay requirements, the most promising is the fully centralized option, with BBU performing baseband processing at three layers from layer 1 (i.e., physical) to layer 3. It makes the most efficient use of the radio resources based on cross-layer optimization while considering multi-RAT availability. BBU centralization makes cooperation and synchronization of RRHs feasible for sending data to users positioned in close pico-, micro-, and macrocells with coordinated multi-point (CoMP), which enables better resource utilization due to reduction of inter-cell interference.

To enable *collaborative media streaming*, this work introduces new functional modules into the BBU to exploit any possible transmission method available at a given time, even by using the D2D connection between neighboring terminals. The BBU functional architecture extended with the proposed collaborative media streaming modules is presented in Fig. 2. It covers modules that perform protocol processing for the supported RAT family controlled by a *radio resource allocation* (RRA) entity. RRA implements multilayer (L1 to L3) and multi-RAT coordination for attaining high

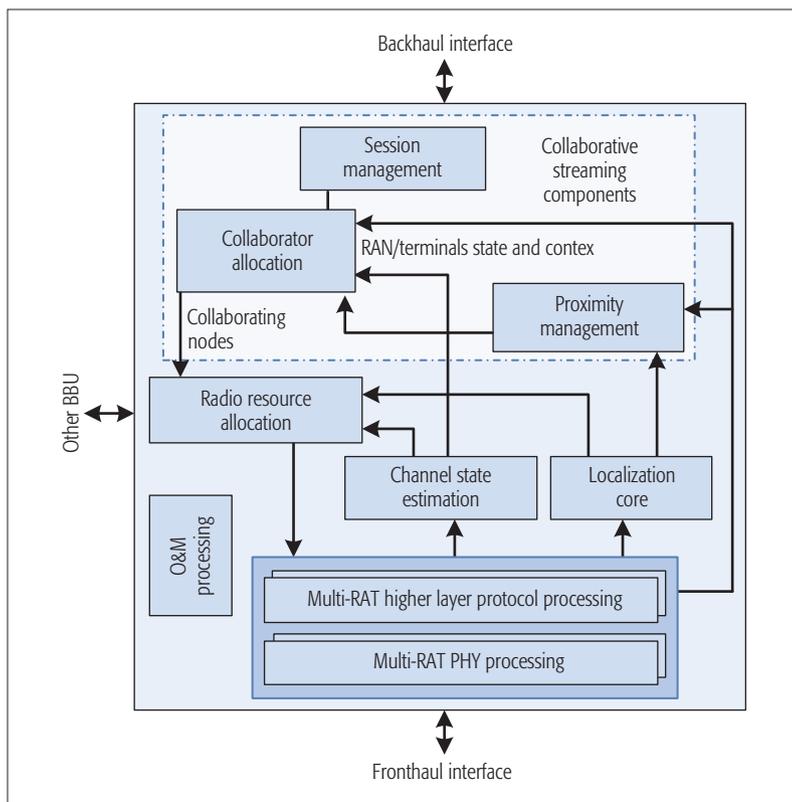


Figure 2. Enhancement of BBU architecture for collaborative media streaming.

spectral efficiency and throughput as well as load balancing mechanisms between cells, and exploits information about terminals' physical locations, obtained from a *localization core*, which may provide highly accurate device geolocation [11].

The new components control the whole collaborative media streaming process, from finding the appropriate collaborator to assigning data to the proper path (directly to the destination terminal of the neighboring device). The collaborative streaming control layer in BBU involves a *proximity management* module that dynamically decides which devices/terminals can operate as neighbors, considering their physical location, but also the devices' capabilities, including available wireless interfaces (usable for direct connections), battery status, and so on. Moreover, collaborative streaming components on different BBUs of the pool interact to discover which terminals are associated with different base stations and which ones could establish a direct connection with each other.

When *proximity management* determines the set of potential neighbors, it passes information about them to *collaborator allocation entities*. Furthermore, the BBU sends (to *collaborating terminals*) a command initiating the monitoring of the state of potential D2D connections. Measurement reports from the terminals are collected by a *channel state estimation* module, which provides (to *collaborator allocation*) information about current channel state for each D2D link (registered in the *collaborator allocation* with a separate ID). Consequently, the *collaborator allocation* decides which devices, from a set of neighbors, can be currently used as collaborators in media streaming. The *collaborator allocation* module indicates to the RRA

which devices are paired as neighbors.

The *session management* module controls media sessions at the BBU. Media sessions are supposed to be transported by HTTP-based adaptive streaming protocols, which are the most common solutions in the current Internet (e.g., Adobe Dynamic Streaming, Apple's HTTP Live Streaming, Microsoft's IIS Smooth Streaming and Dynamic Adaptive Streaming over HTTP – DASH). Their most interesting feature is the capacity of adapting the streaming bit rate to the state of the transportation path for the flow. The file ordering all the HTTP segments (the fragments of video are independently callable with their own URLs) is the manifest file.

Session management identifies a new media session start by recognizing the manifest file downloaded by a user; it analyzes the file, and becomes aware of the different fragments of video (called chunks or segments) and the bandwidth necessary for their transmission. Next, when the module detects a segment request from the user, it asks *collaborator allocation* if additional bandwidth for a given user could be available through collaboration. After checking the potential collaborators and selecting the appropriate one/s, *Session management* informs the user about how to request the content fragments from collaborating devices and, concretely, sends information containing the URLs to request the content fragments through different paths. Let us remark that the content fragments are short in HTTP-based adaptive streaming (2 to 10 seconds), which avoids problems of device mobility due to very short session duration. When a collaborator receives the request through a D2D link, it redirects the request to a BBU, and the request is further handled by the session management module in the BBU.

To speed up the media streaming process, *session management* may work as a caching entity and, based on information provided by the manifest file, downloads (in advance) a small number of portions of video with best quality (higher bit rate) from the content server. In this way, the module responds to a user or collaborators just after receiving media requests, using a priori cached data, to reduce media delivery latency. This solution is also open to other caching solutions [9, 12].

TERMINAL ARCHITECTURE FOR COLLABORATIVE APPLICATIONS

This section presents the functionalities required in the end users' terminals in order to provide collaboration in media streaming upon acceptance of the end users (agreement for collaboration in media streaming).

In the proposed solution, the process of finding adjacent devices and establishing D2D links is fully BBU controlled; the BBU has a view of the entire access domain, so it can optimize the selection of neighbors and RAT used for D2D connection. In this way, D2D connection establishment is fast and resource-efficient, whereas neighbor discovery performed solely by terminals (as occurs in overlay solutions) is energy- and time-consuming. Last but not least, the network operator performs authentication of collaborating devices, which

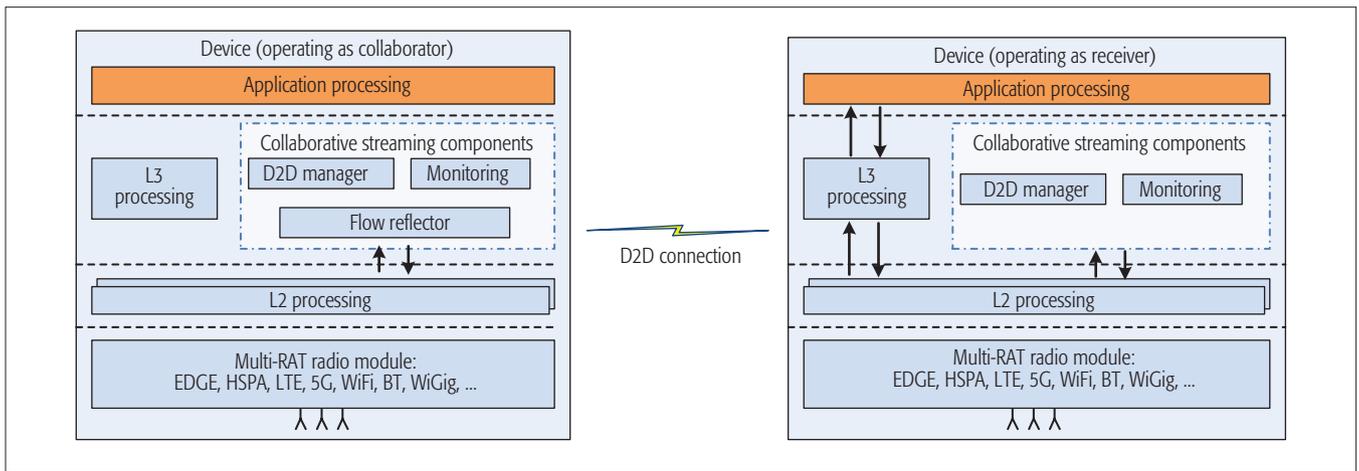


Figure 3. Architecture of client devices for collaborative streaming.

is important from the point of view of security and privacy. Nonetheless, the set of neighboring devices is restricted to only a given operator's clients, which limits the number of potential collaborators. This drawback can be overcome by proper cooperation and collaboration of different network operators (cellular and wireless), intended to form one ecosystem to cover a smart city area.

Figure 3 shows the high-level architecture of the 5G user device (each might be capable to simultaneously use multiple RATs) for collaborative streaming, which can play two roles: a collaborator or a media receiver. The *D2D manager* establishes and terminates D2D links through the RAT indicated by a BBU and manages D2D connections in all the lower layers. For example, at the medium access control (MAC) layer, the *D2D manager* sends and receives measurement packets, in the appropriate RAT, for monitoring direct link conditions. The *monitoring* module receives this information and estimates the quality of service (QoS) metrics for a given direct link, such as estimated bandwidth and packet losses. Measured QoS metrics, as well as contextual information (mainly available wireless interfaces and state of the battery), are transmitted from the *monitoring* module to the associated BBU.

A collaborator contains a *flow reflector* to play the role of a proxy in communication between the receiver and associated BBU. The module parses the request generated by the receiver, replaces its own address with the BBU's address in the request, and then transfers it to the BBU. Next, it redirects the BBU's response, which carries the requested content, to the receiver using D2D connection.

RESOURCE CONTROL

Resource control functionality is crucial for the performance of collaborative media streaming due to the high requirements of multimedia content. This section presents the framework between BBU and terminals in order to support efficient collaboration between terminals. Collaborative streaming is a different scenario comparing to conventional D2D approach, where two devices (the source and the destination) control the end-to-end communication. On the contrary, collaborative streaming is managed by an entity different to the devices (i.e., the BBU), and the content

source is usually in the Internet. Consequently, all involved devices (i.e., the collaborators and the receiver) have to set up a connection with their base stations. In the in-band approach the resource control algorithm takes care to allocate separate resources (frequency, time slots) to D2D links and conventional cellular links. If the out-of-band D2D solution is adopted, the resource control algorithm should prefer in the collaborator selection process those terminals that are able to establish direct links by RATs other than the RAT used in the primary downlink (from the base station) to avoid co-channel interference.

The sequence of operation is as follows. First, the BBU selects a set of possible collaborators (after receiving information on the localization of terminals) and sends information about them to the target end user's terminal (receiver). Moreover, the BBU establishes D2D connections with indicated collaborators and sets parameters for the D2D link such as maximum allowed signal strength and parameters of D2D radio in case of licensed spectrum (frame number, system bandwidth, synchronization information, etc.). The 5G radio resource control (RRC) signaling protocol is used for this communication, and each active collaborator is in an RRC-connected state with bidirectional communication with the BBU. The collaborating terminal measures direct link parameters (estimated bandwidth and wireless interface usage) and sends them to the BBU. The collaborating terminal sends the BBU the D2D connection measurements together with the following device information: RATs supported by the device, CPU usage, available energy, estimated bandwidth available in the downlink (from base station to terminal), last locations of the terminal for predicting the terminal trajectory, and terminal activity (i.e., if the terminal is involved in other collaborative streaming sessions). At last, the BBU processes all the information and performs selection of terminals in collaboration with the scope of the given media session. In advanced RAN architectures [9], RRA might be supported by information provided by external actors through open interfaces provided by mobile edge computing technology in order to select the best collaborators [13].

The optimization objectives of the terminal selection algorithm can vary according to the

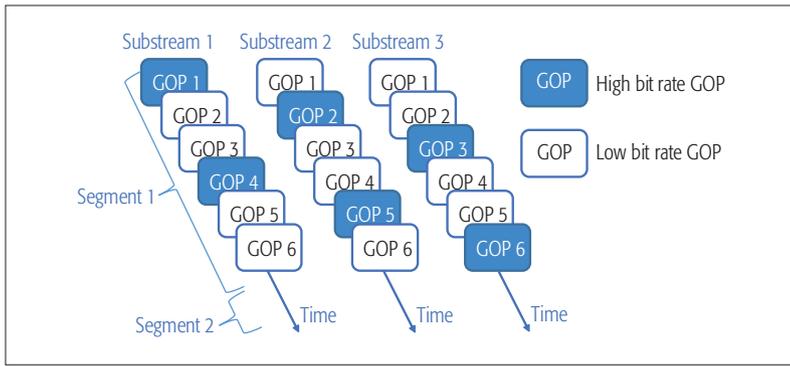


Figure 4. MD-DASH scheme: substream creation strategy.

service provider's policies and/or user requirements and expectations. Example policies are: to maximize overall media throughput, to maximize throughput while minimizing power consumption (in this case, the algorithm should avoid power-consuming D2D connections, even if they provide higher bandwidth), and to maximize overall user quality of experience, QoE (e.g., one should avoid too frequent variation of media streaming bit rate in adaptive streaming).

The resource control algorithm implemented by the *collaborator allocation module* is a complex optimization task performed by the BBU pool. We use a two-phase evolutionary multi-objective optimization algorithm that we previously proposed in [14]. This algorithm enables the finding of several solutions belonging to the Pareto frontier (several collaborators) instead of one unique solution (other multi-criteria decision algorithms aim to find one unique solution).

CONTENT ENCODING FOR COLLABORATIVE MEDIA STREAMING

This section presents the solution adopted for multipath streaming, which is necessary in a collaborative scenario. The multipath streaming protocol is installed in the server and the receiver at the application level over HTTP and runs independently of the other modules of collaborative streaming (only the *collaborator allocation* informs the proxy server about the state of the paths). The protocol is transparent to the collaborators.

The proposed solution is compliant with adaptive streaming. In fact, proposed Multiple Description – Dynamic Adaptive Streaming over HTTP (MD-DASH) is an extension of DASH and fully compliant with the standard. The main advantage of MD-DASH in comparison to the other multi-path streaming protocols is that it retains an adaptive feature, which makes implementation in current networks feasible. Moreover, MD-DASH is easily implementable in current applications (since only the adaptation protocol library should be extended) and does not require excessive overhead.

DASH defines the video content as being divided into a subset of chunks (called segments) and encoded at multiple bit rates (all the content segments encoded with the same nominal bit rate belong to the same representation). The client application requests each segment independently (new HTTP request), and for each segment, it selects the best representation that may be

streamed in current network conditions by analyzing the download of the last segments.

The idea of MD-DASH is to interleave groups of pictures (GOPs) that belong to higher and lower representations, creating a substream, with mean bit rate between lower and higher representative bit rates. Each substream is fully decodable and viewable (so synchronization of substreams is not mandatory); however, the playing out of one unique substream offers suboptimal QoE to the viewer since some parts of the content will be played at higher quality than others. The playout of all different substreams together offers optimal QoE due to the capacity of the MD-DASH client to select from each substream the best-quality GOPs, discarding the lower-quality ones.

The GOPs are encoding operation units used in current (H.264) and upcoming (H.265) codecs. One GOP contains a video of the same scene, such that the encoding operations inside one GOP are highly correlated, which improves the possibility-to-compression ratio. Figure 4 shows MD-DASH triple substream creation based on two different representations, each substream transmitted through a different path within the network.

The high bit rate GOPs contain high-definition information of the video, whereas low bit rate GOPs contain the minimum video information necessary for playing the video at lower quality. Therefore, the overhead introduced by MD-DASH is low (and equals the relation between low and high bit rate GOPs, as indicated in [15]). The adaptation algorithm in the client application decides about the representation to be downloaded for each segment, and this request is sent to the BBU.

Substream creation is performed on the servers of the BBU cloud when the *collaborator allocation* reports the number of available collaborators (say N) and the available bandwidth of each D2D link, in such a way that the bit rate of the best quality GOPs selected from the substreams corresponds to the representation bit rate indicated by the client application (at the receiver) included in the HTTP request message. In the case that all N paths have similar downlink capacity, the N substreams will contain a similar number of high bit rate GOPs. However, in the case in which the N paths have different bottleneck bit rates, the substream for each path will be adapted to the path bottleneck. Substream creation is a lightweight operation that may be performed in real time by a medium class server.

We evaluated our MD-DASH implementation by considering the perceived quality at the consumer's side (i.e., QoE). To this end, we monitored and evaluated two criteria considered as essential for the QoE of video streaming services: the number of rebuffering events and the quality distribution throughout the streaming session. Collaborative multipath streaming with MD-DASH is compared to two other scenarios: unipath adaptive streaming (no collaboration; the content is downloaded directly from the BBU server; this is the case of current downloading on the Internet) and multipath streaming without adaptation (the content is downloaded through three different paths, but the client application is not able to adapt the content bit rate to the network state).

#1 Mb/s (ms;%)	#2 Mb/s (ms;%)	#3 Mb/s (ms;%)	#4 Mb/s (ms;%)	#5 Mb/s (ms;%)	#6 Mb/s (ms;%)
5.0 (38;0.09)	5.0 (13;0.81)	5.0 (11;1.00)	9.0 (25;0.06)	9.0 (10;0.40)	9.0 (6;1.00)
4.0 (50;0.08)	4.0 (18;0.63)	4.0 (13;1.25)	4.0 (50;0.07)	4.0 (50;0.08)	4.0 (13;1.25)
3.0 (75;0.06)	3.0 (28;0.44)	3.0 (15;1.50)	2.0 (75;0.10)	2.0 (150;0.03)	2.0 (20;1.50)
2.0 (88;0.09)	2.0 (58;0.21)	2.0 (20;1.75)	1.0 (100;0.16)	1.0 (200;0.07)	1.0 (25;2.00)
1.5 (100;0.12)	1.5 (200;0.03)	1.5 (25;2.00)	2.0 (88;0.09)	2.0 (150;0.03)	2.0 (20;1.50)
2.0 (88;0.09)	2.0 (58;0.21)	2.0 (20;1.75)	3.0 (75;0.06)	4.0 (50;0.08)	4.0 (13;1.25)
3.0 (75;0.06)	3.0 (28;0.44)	3.0 (15;1.50)	4.0 (50;0.08)		
4.0 (50;0.08)	4.0 (18;0.63)	4.0 (13;1.25)			

Table 1. Network profiles (from DASH standard).

In this last case, the 10-minute Big Buck Bunny movie was encoded in three substreams (containing 33 percent of GOPs at 6 Mb/s and 66 percent of GOPs at 200 kb/s). In the other cases, the movie was encoded at 7 different bit rates in H.264 (200 kb/s, 1 Mb/s, 1.5 Mb/s, 2 Mb/s, 3 Mb/s, 4 Mb/s, and 6 Mb/s), and the client adaptation algorithm selected the best acceptable representation for each segment download. In multipath adaptive (i.e., MD-DASH), the lower bit rate GOPs were 200 kb/s-encoded in order to minimize overhead. The MD-DASH substreams were created based on the information about the state of the three paths between the server and the end user's terminal (i.e., the mean encoding bit rate of the substream to be downloaded was equal to the bandwidth in the path). Such information was provided by the *collaborator allocation* module. The client implementation of unipath adaptive, multipath non-adaptive, and MD-DASH streaming clients were based on dash.js player.

The DASH Industry Forum provides benchmarks for various aspects of the DASH standard. The benchmarks include 12 different network profiles (NPs) featuring different bandwidths, delays, and packet loss. We used only six of them (marked as #Number in Table 1). Each profile spends 30 s for each step described in Table 1, then starts back at the beginning. For each experiment, a specific NP is associated with all paths between the client and the BBU server. A random time offset is set to each assigned NP to represent bandwidth diversity and variability in the network. Each video was repeated 40 times per application and per NP, and a total playback time of 120 h was performed.

Unipath adaptive streaming delivered content with lower quality than multipath streaming due to single-path bandwidth limitations; nonetheless, it reached no rebuffering situations during the 10 min experiments thanks to the bit rate adaptation feature. Instead, multipath non-adaptive streaming suffered constant rebuffering, making the viewing of the content very unpleasant. In fact, multipath the non-adaptive client observed between 0.12 and 1.22 rebuffering situations per streaming session on NPs #1-#2-#3 and between 2.76 and 4.08 on NPs #4-#5-#6 (Fig. 5b).

MD-DASH performed a trade-off between content quality and network availability in multiple paths. Besides, the adaptation mechanisms in MD-DASH allowed the client to take benefit of download bandwidth and eventually provided the 6 Mb/s top quality for 84 percent of the time on average on all NPs (Fig. 5a). In terms of quality distribution over the streaming session, MD-DASH

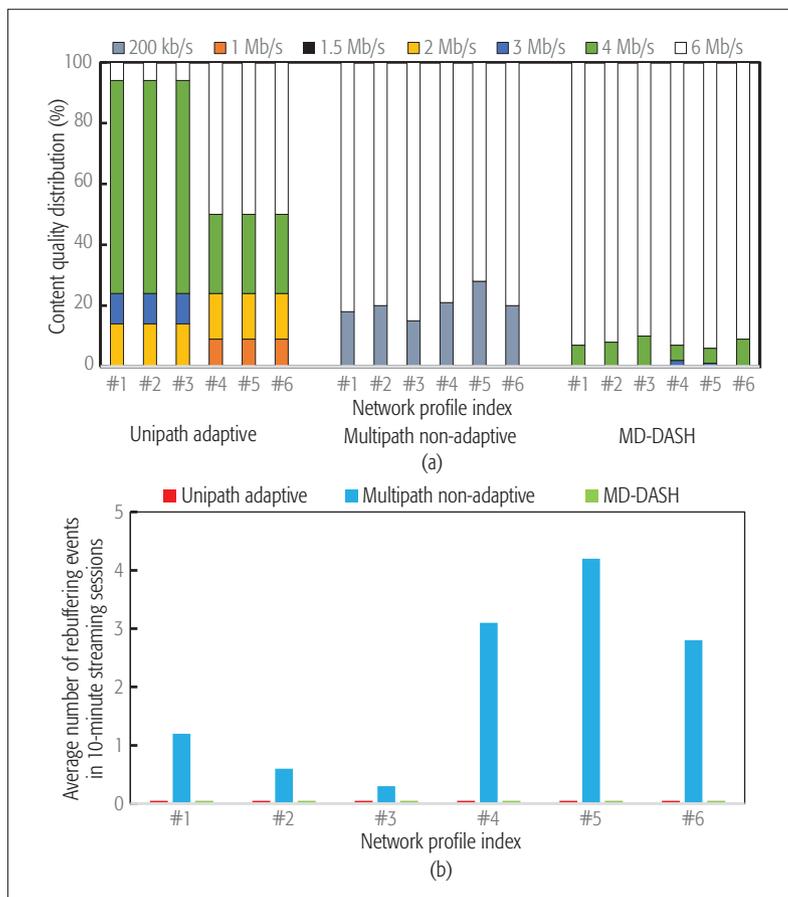


Figure 5. Quality of experience results: a) quality representation throughout streaming session; b) averaged number of rebuffering events.

performed significantly better than unipath thanks to the simultaneous usage of collaborators and even better than multipath non-adaptive streaming since MD-DASH adapted the bit rate to each path condition. Moreover, MD-DASH avoided buffer depletion on all NPs.

These results demonstrate the asset of multipath collaborative media and adaptive streaming in terms of QoE in contrast to current media downloading on the Internet.

CONCLUSIONS

This article presents a solution for growing media delivery throughput in dense heterogeneous wireless networks. It is based on the collaboration of terminals in proximity for providing multipath delivery of media segments. Multipath transmission is well suited to increase efficiency

With such a network-aware approach, content characteristics can be fit to current radio conditions. The results obtained in the implementation of the system show that multipath adaptive streaming clearly overcomes both unipath adaptive and multipath non-adaptive streaming.

in future 5G systems, which respond to smart city requirements for communication infrastructure. We describe new modules designated for user devices as well as for centralized RAN to allow collaboration. At the client side, such modules are responsible for establishing and managing D2D links. They also implement mechanisms of relaying data between the media receiver and the network. On the other hand, modules introduced to the BBU are responsible for selecting appropriate collaborators and optimal resource allocation.

Multipath delivery in C-RAN enables the use of novel MD-DASH streaming technology, which assumes generating a number of substreams transferred to the receiver through different paths. The more substreams reach the user's terminal, the higher QoE will be perceived by the user during media consumption. In the presented system, the process of substream creation is performed using computing capabilities provided by the C-RAN, in accordance with the instructions from the BBU collaborator allocation. With such a network-aware approach, content characteristics can be fit to current radio conditions. The results obtained in the implementation of the system show that multipath adaptive streaming clearly overcomes both unipath adaptive and multipath non-adaptive streaming.

ACKNOWLEDGMENTS

The work presented in this article is co-funded by the European Union, Celtic-Plus Programme, under the project C2015/4-5, MONALIS: monitoring and control of QoE in large-scale media distribution architectures.

REFERENCES

- [1] R. Yu *et al.*, "Enhancing Software-Defined RAN with Collaborative Caching and Scalable Video Coding," *Proc. IEEE ICC*, Kuala Lumpur, Malaysia, 2016, pp. 1–6.
- [2] N. Golrezaei *et al.*, "Femtocaching and Device-to-Device Collaboration: A New Architecture for Wireless Video Distribution," *IEEE Commun. Mag.*, vol. 51, no. 4, 2013, pp. 142–49.
- [3] M. Zhong *et al.*, "ColStream: Collaborative Streaming of On-Demand Videos for Mobile Devices," *Proc. IEEE 15th Int'l. Symp. on a World of Wireless, Mobile and Multimedia Networks*, Sydney, Australia, 2014, pp. 1–7.
- [4] E. Toledano *et al.*, "CoCam: A Collaborative Content Sharing Framework Based on Opportunistic P2P Networking," *Proc. IEEE 10th Consumer Commun. Networking Conf.*, Las Vegas, NV, 2013, pp. 158–63.
- [5] Y. Zhang, L. Chao, and S. Lifeng, "DECOMOD: Collaborative DASH with Download Enhancing Based on Multiple Mobile Devices Cooperation," *Proc. 5th ACM Multimedia Sys. Conf.*, Singapore, 2014, pp. 160–63.
- [6] L. Zhang *et al.*, "Green and Cooperative DASH in Wireless D2D Networks," *Wireless Personal Commun. J.*, vol. 84, no. 3, 2015, pp. 1797–1816.
- [7] D. Syrivelis *et al.*, "Bits and Coins: Supporting Collaborative Consumption of Mobile Internet," *Proc. IEEE INFOCOM*, Kowloon, China, 2015, pp. 2146–54.
- [8] A. Checko *et al.*, "Cloud RAN for Mobile Networks — A Technology Overview," *IEEE Commun. Surveys & Tutorials*, vol. 17, no. 1, 2015, pp. 405–26.
- [9] M. Patel *et al.*, "Mobile-Edge Computing Introductory Technical White Paper," ETSI, 2014; https://portal.etsi.org/Portals/0/TBpages/MEC/Docs/Mobile-edge_Computing_-_Introductory_Technical_White_Paper_V1%2018-09-14.pdf (accessed September 2016)
- [10] M. Sheng *et al.*, "Video Delivery in Heterogenous CRANs: Architectures and Strategies," *IEEE Wireless Commun.*, vol. 22, no. 3, 2015, pp. 14–21.
- [11] A. Hakkarainen *et al.*, "High-Efficiency Device Localization in 5G Ultra-Dense Networks: Prospects and Enabling Technologies," *Proc. IEEE 82nd VTC-Fall*, Boston, MA, 2015, pp. 1–5.
- [12] X. Wang *et al.*, "Cache in the Air: Exploiting Content Caching and Delivery Techniques for 5G Systems," *IEEE Com-*

mun. Mag., vol. 52, no. 2, 2014, pp.131–39.

- [13] J. O. Fajardo, I. Taboada, and F. Liberal, "Improving Content Delivery Efficiency through Multi-Layer Mobile Edge Adaptation," *IEEE Network*, vol. 29, no. 6, 2015, pp. 40–46.
- [14] J. M. Batalla *et al.*, "Evolutionary Multiobjective Optimization Algorithm for Multimedia Delivery in Critical Applications through Content Aware Networks," *J. Supercomputing*, 2016, pp. 1–24.
- [15] J. Bruneau-Queyreix *et al.*, "Multiple Description-DASH: Pragmatic Video Streaming Maximizing End-Users' Quality of Experience," *IEEE ICC*, Kuala Lumpur, Malaysia, 2016, pp. 1–7.

BIOGRAPHIES

JORDI MONGAY BATALLA (J.Mongay@itl.waw.pl) is the head of the Internet Technologies and Applications Department at the National Institute of Telecommunications, Poland. He is also with Warsaw University of Technology (WUT), where he is an assistant professor and provides research on Internet protocols and applications, especially multimedia delivery, Internet of Things, and cloud/edge computing. He has written more than 100 research papers in renowned international journals and conferences, and is on the Editorial Boards of several journals.

PIOTR KRAWIEC (P.Krawiec@itl.waw.pl) received a Ph.D. degree in telecommunications from WUT in 2011. He is an assistant professor in the Internet Technologies and Applications Department at the National Institute of Telecommunications and concurrently holds a research position at WUT. His research interests lie in the areas of multimedia delivery, streaming protocols, wireless communications, and the Internet of Things.

CONSTANTINOS X. MAVROMOUSTAKIS [SM] (mavromoustakis.c@unic.ac.cy) is currently a professor in the Department of Computer Science at the University of Nicosia, Cyprus, where he leads the Mobile Systems Lab. He has been a Vice-Chair of the IEEE/R8 regional Cyprus section since January 2016, and since May 2009 has served as the Chair of the C16 Computer Society Chapter of the Cyprus IEEE section. He has a dense research work outcome (more than 220 papers) in distributed mobile systems and spatio-temporal scheduling, consisting of numerous refereed publications including several books, and he has served as Track Chair and Co-Chair of various IEEE international conferences.

GEORGE MASTORAKIS (mastorakis@gmail.com) received his B.Eng. degree from the University of Manchester, his M.Sc. from University College London, and his Ph.D. from the University of the Aegean. He is an associate professor at the Technological Educational Institute of Crete and a research associate at the Centre for Technological Research of Crete. His research interests include cognitive radio networks, network traffic analysis, and radio resource management.

NAVEEN CHILAMKURTI (N.Chilamkurti@latrobe.edu.au) is currently acting head of the Department of Computer Science and IT, La Trobe University, Melbourne, Australia. He is also the Inaugural Editor-in-Chief for the *International Journal of Wireless Networks and Broadband Technologies*. He is currently serving as a Technical Editor for *IEEE Wireless Communications* and *IEEE Communications Magazine*. He has published about 190 journal and conference papers. His current research areas include cybersecurity, IDS, authentication, wireless sensor networks, and more.

DANIEL NEGRU (daniel.negru@labri.fr) received his Ph.D. from the University of Versailles Saint Quentin, France, in 2006 in the field of communication networks. In 2007, he became an associate professor at the University of Bordeaux, France, specializing in multimedia and networking. He has participated in more than 10 collaborative research projects at the European level and published more than 60 papers, including high-level ones in prestigious journals and conferences, such as *IEEE Communications Magazine*, *IEEE Multimedia*, *GLOBECOM*, *ICC*, and *FIA*.

JOACHIM BRUNEAU-QUEYREIX (jbruneauqueyreix@viotech.net) received his M.Sc. in telecommunications at ENSEIRB-MATMECA graduate school of engineering, Bordeaux, in 2014. Since then, he has pursued his Ph.D. at the University of Bordeaux in the field of multi-criteria optimization for content delivery within the future media Internet. His research interests include video codecs, streaming protocols, systems and architectures, multimedia streaming prototyping, and network functions virtualization. He has joined three European research projects in the field of ICT (FP7, CHIST-ERA, and EUREKA).

EUGEN BORCOCI (Eugen.Borcoci@elcom.pub.ro) is a professor in the Department of Electronics, Telecommunications, and

Information Technology of University Politehnica of Bucharest, Romania. His expertise comprises theoretical and/or experimental knowledge in telecommunication/computer systems and networks: architectures and protocols, multicast and multimedia services, and network and services management. His recent areas of interest are future Internet architectures, networked media and QoS/QoE, content-aware networking, software defined networking and network functions virtualization, and 5G technologies. He has participated as team leader and researcher in many FP5, FP6, FP7, and Chist-Era European projects.