Abstract

End users and governments are forcing network operators to deploy faster Internet access services everywhere. Access technologies such as FT Tx, VDSL2, and DOCSIS3.0 can provide such services in cities. However, it is not cost-effective for network operators to deploy them in less densely populated regions. The recently proposed hybrid access networks allow boosting xDSL networks by using the available capacity in existing LTE networks. We first present the three architectures defined by the Broadband Forum for such hybrid access networks. Then we describe our experience with the implementation and deployment of Multipath TCP-based hybrid access networks.

Introduction

Network operators have deployed a variety of fixed access network technologies (xDSL, DOCSIS, FT Tx, etc.) and various wireless technologies (3G, 4G, FWA, and soon 5G). Today’s bandwidth-hungry applications like video streaming and various cloud services have forced network operators to increase the capacity of their access networks. Over recent decades, various improvements have been brought in digital subscriber line (DSL) networks. While the initial deployments offered bandwidths of only a few megabits per second, current deployments with VDSL2 and G.Fast have reached hundreds of megabits per second or more. Both VDSL2 and G.Fast can reach their peak bandwidth when households are close to street cabinets (from hundreds of meters for G.Fast to 1 km for VDSL2). These technologies are effective in dense areas where fiber has been deployed close to the end users. However, there are many regions, such as rural areas, where xDSL cannot reach its optimal bandwidth due to signal loss on long copper pairs.

Governments in Europe, America, and Asia have announced ambitious objectives to provide better broadband services to their entire population. In Europe, the objective is to provide 30 Mb/s to all Europeans by 2020. In the United States, broadband is defined as 25 Mb/s in downstream and 3 Mb/s in upstream.

The European Commission defines the Next Generation Access (NGA) as fixed-line broadband access technologies capable of achieving download speeds meeting the Digital Agenda objective of at least 30 Mb/s coverage [1]. Based on data from the 28 countries of the European Union, DSL is the most widespread non-wireless technology in rural areas with a coverage of 86.3 percent in 2017, but it is not considered as an NGA. VDSL is only available in 32.5 percent of rural areas. FTTP, cable, and DOCSIS barely reach 10 percent of coverage in these areas. On the other hand, Long Term Evolution (LTE) covered 89.9 percent of the rural areas across Europe in 2017. The latest measurements reported by the Federal Communications Commission (FCC) in the United States [2] indicate that only 92.3 percent of the population has access to a fixed terrestrial service at 25 Mb/s. At 50 Mb/s, this number drops to 90.8 percent of the population.

To cope with these government objectives, network operators deploy NGA technologies in densely populated areas such as cities. However, this deployment takes time and will still require several years to complete. In rural areas, NGA technologies are barely economically viable given the population density. This has encouraged network operators to explore alternatives. One of them is to combine a terrestrial broadband access network such as xDSL with a wireless access network such as LTE. The combined availability of xDSL and LTE opens new opportunities for the network operators that own these two types of networks. The hybrid access networks discussed in this article make it possible to combine the existing xDSL network with an existing wireless network such as LTE to provide higher-bandwidth services. This enables network operators to provide faster Internet access services without the costly fiber rollouts that are required by solutions such as VDSL2 and G.Fast.

During the last few years, hybrid access networks have moved from lab prototypes to large-scale deployments of standardized solutions. Standards are important for network operators because they allow solutions from different vendors to interoperate. We first describe in the section below the reference architectures and the key protocols that the Broadband Forum (BBF) has specified to build hybrid access networks, presenting two solutions: one based on tunnels and the other one on Multipath TCP (MPTCP). The third section analyzes measurements of the key components of such networks and provides feedback on real deployments.

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Network operators rely on different standardized technologies to offer broadband services to their subscribers. Standards have become a prerequisite for large-scale deployments of access network solutions by network operators. The BBF initiated architectural work that was finalized in 2016 [3] while the work on the protocols was progressing within the Internet Engineering Task Force (IETF). In 2019 the BBF finalized the Nodal Requirements for Hybrid Access Broadband Networks [4] that leverage recent IETF specifications [5-7].

HYBRID ACCESS ARCHITECTURE

To understand how hybrid access networks will be deployed, it is important to first understand their architecture. A classical access network includes subscribers’ clients using Wi-Fi or Ethernet connected to customer premises equipment (CPE). The latter is then connected to the operator’s network through one of the technologies discussed in the previous sections, which provides Internet access. In a typical xDSL deployment, the CPE receives an IP address from the DSL provider. For simplicity, we consider in this section that addresses are allocated to the CPE by the network without discussing the differences between IPv4 and IPv6. We use the @ symbol to represent such an address.

Now, let us consider what happens when the CPE is attached to both xDSL and LTE networks as in Fig. 1. We call such CPE hybrid CPE (HCPE) in this article. From an addressing viewpoint, there are two possible architectures to connect these HCPEs to the network. A first approach is to configure the address allocation function in both the xDSL and LTE networks to allocate the same address on both links (i.e., addresses @cpe1 and @cpe2 in Fig. 1 are equal). In this case, the HCPE is reachable through the same address over the two networks. The HCPE and the network can load-balance the packets over the two access links at any time. They could use per-flow load balancing, where each UDP flow or TCP connection is associated with one access link and all the packets belonging to this flow are sent over this link only, or a per-packet load balancing strategy, where packets belonging to a single TCP connection can be sent over different access networks, which in practice leads to reduced performance due to TCP collapse.

From an address allocation viewpoint, the simplest solution to connect the HCPE to both the xDSL and LTE networks is to allocate a different address on each access link. An important point to note about this address allocation is that network providers usually implement network ingress filtering to prevent spoofing attacks. The consequence of network ingress filtering is that if address @a1 (resp. @a2) has been assigned on the xDSL link (resp. the LTE interface), only the packets whose source address is equal to @a1 (resp. @a2) can be sent over the xDSL link (resp. the LTE interface). If the HCPE sends a packet whose source address is @a2 on the xDSL link, it will be discarded by the provider.

Given that two different addresses are assigned to the HCPE, a simple mechanism would be to assign these two addresses to the hosts attached to the HCPE. IPv6 implementations can associate several IPv6 addresses to a single interface, but with IPv4, this is more difficult as DHCP allocates several IPv4 addresses to a single host. However, having several addresses per host would not solve our problem.

When a host has several addresses, it selects one of them every time it needs to establish a flow. This implies that a given flow will be transported over a single access network and will have no way to utilize the two access links simultaneously. An issue for network operators is that hosts can autonomously select their access link by selecting their source address. This makes it impossible for them to implement policies to prioritize the use of one access network over the other.

Given the importance of hybrid access networks, several solutions have been explored by BBF and IETF to solve the above-mentioned problems. Three of them are defined in the recent BBF TR-378 specification [4]. They focus on three key requirements:

1. Supporting per-packet load balancing to be able to efficiently utilize two different access links for a single TCP connection
2. Assigning a single address to the end hosts attached to the HCPE
3. Supporting network ingress filtering

They all rely on the utilization of a special network function called the hybrid access gateway (HAG), which is deployed by the network operator. Figure 1 describes the architecture of such hybrid access networks. We assume an HCPE that is attached to both DSL and LTE networks. It

![Figure 1. The architecture of hybrid access networks.](image-url)
has received one address from each network (@cpe1 was allocated by the DSL network, and @cpe2 was allocated by the LTE network). A single address is assigned to each connected host. We also assume that the HAG is reachable via two addresses (@h1 via the DSL network and @h2 via the LTE network).

**GRE-Based L3 Overlay Tunneling**

The first realization of this architecture relies on generic routing encapsulation (GRE) tunnels [4, 6]. This solution can be summarized as follows. The HCPE is reachable via two different addresses (@cpe1 and @cpe2 in Fig. 1), which are not directly exposed to the hosts, but are only to create tunnels toward the HAG. The HCPE has a third address that it assigns to its attached host. When a host initiates a TCP connection, it sends the first packet to the HCPE. The HCPE encapsulates it in one of its GRE tunnels and sends it to the HAG, which decapsulates the packet and forwards it to its final destination. The server response reaches the HAG, which maps it to its associated HCPE and encapsulates it in one of the tunnels that reaches the HCPE. The HCPE decapsulates the packet and forwards it to the client host. Both the HCPE and the HAG and the HCPE can use per-packet load balancing to distribute the load over the two access networks. The solution specified in BBF WT-378 [4] includes several extensions to the basic GRE. Additional details are provided in [6]. Some lessons learned from the deployment of tunnel-based hybrid access networks have been discussed in IETF presentations [8].

**4.1 Multipath Using MPTCP**

The two other standardized architectures rely on Multipath TCP [5]. Multipath TCP is a recent TCP extension that enables hosts to use different paths to exchange packets belonging to a single TCP connection. Multipath TCP includes several mechanisms that enable hosts to efficiently utilize different networks [9]. A Multipath TCP connection starts with a three-way handshake like a regular TCP connection. To inform the server of its willingness to use Multipath TCP, the client inserts the MP_CAPABLE option in the first SYN packet. This option contains a 64-bit key that is associated with this specific connection. The server replies with a SYN+ACK that also contains an MP_CAPABLE option. The client replies with an ACK packet that also contains the MP_CAPABLE option [5]. At this point, the Multipath TCP connection is established over the path used by the SYN packets, and both the client and the server can send data. Multipath TCP supports an ADD_ADDR option that enables a host to advertise its other addresses to the remote host. To use another path, the client or the server must create a TCP subflow along this path. This is done by sending a SYN packet that contains the MP_JOIN option. Thanks to the content of this option, the server can associate the subflow establishment attempt with an existing Multipath TCP connection and authenticate it during the three-way handshake that creates the subflow. Once the subflow has been established, data can flow over any of the available paths. Thanks to its congestion control schemes, Multipath TCP can react efficiently to congestion on the different paths [9]. Furthermore, Multipath TCP uses its own sequence numbers to reorder the packets sent over different paths at the receiver, but also to allow packet reinsertion from one path to another one, for example, upon timeout on an initially attempted path [9].

With Multipath TCP, an end host could efficiently use the different paths that exist in hybrid networks. Unfortunately, although several implementations of Multipath TCP exist [10], they are not used on popular end hosts or servers. To still benefit from the unique capabilities of Multipath TCP, BBF has decided to rely on Multipath TCP proxies. A Multipath TCP proxy is a network function that converts Multipath TCP connections into TCP connections and vice versa. It can be installed on HCPEs and HAGs. In the implicit deployment [4], the HAG is located on the forwarding path between the HCPE and the Internet on the xDSL network (Fig. 1). Figure 2 provides a sequence diagram of the establishment of a TCP connection using this implicit deployment. When a host attached to an HCPE initiates a connection, it sends the first packet to the HCPE. The Multipath TCP proxy running on the HCPE intercepts the TCP connection establishment attempt (SYN packet) and replaces it with a Multipath TCP connection establishment attempt (SYN+MP_JOIN packet). This packet is forwarded along the DSL network, and the HAG intercepts it. The HAG performs the reverse operation and forwards a connection establishment attempt toward the final destination. The destination replies and confirms the connection establishment. This confirmation is intercepted by the HAG, which in reaction confirms the establishment of the Multipath TCP connection to the HCPE, which eventually confirms the establishment of the connection to the host. At this point, the connection between the host and the server is composed of three parts:

- A (regular) TCP connection between the host and the HCPE
- A (Multipath) TCP connection between the HCPE and the HAG
- A (regular) TCP connection between the HAG and the server

At that time, the HAG can advertise its address on the LTE network (i.e., address @h2 on Fig. 1) by using the ADD_ADDR option. With this information, the HCPE can initiate a second subflow over the LTE interface (SYN+MP_JOIN packets exchanged with the HAG).

It should be noted that as both the HCPE and the HAG transparently intercept the TCP connections, they do not need to implement any Network Address Translation function. This deployment supports per-packet load balancing as Multipath TCP continually measures the packet losses and delays over the xDSL and LTE networks, and dynamically adjusts the load over the two paths thanks to its congestion control scheme.

The third approach also leverages Multipath TCP, but the HAG does not need to transparently intercept the Multipath TCP connections proxied by the HCPE. The packet flow is illustrated in Fig. 3. The HCPE still includes a transparent proxy that proxies the TCP connections established by the local hosts. The main difference with the previous deployment is that the HAG is directly reachable through an IP address over the xDSL network (@h1 in Fig. 1). Upon reception of a connection

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establishment packet from a local host toward a remote server, the HCPE sends a Multipath TCP connection establishment packet toward the address of its HAG and places the address of the remote server (i.e., \( s \)) inside the payload of this packet. This leverages the 0-RTT Convert Protocol whose specification is being finalized within IETF [7]. The HAG terminates the Multipath TCP connection and immediately sends a connection establishment packet toward the remote server. As in the previous solution, the HCPE can also create subflows over the LTE network to utilize the two access networks. The connection between the client and the server is composed of three connections that are glued together by the transparent proxy running on the HCPE and the 0-RTT Convert Protocol that is running on the HAG. This is illustrated in Fig. 3.

Besides the standardized solutions described in this section, researchers have explored other approaches to combine heterogeneous access networks. Markus Amend et al. proposed adding multipath capabilities to the Datagram Congestion Control Protocol (DCCP) to notably support the hybrid access use case [11]. This approach combines the benefits of using a congestion control

![Figure 2. The implicit Multipath TCP deployment mode.](image2)

![Figure 3. The explicit Multipath TCP deployment mode.](image3)
scheme, as in the Multipath TCP solutions, with a protocol that transports datagrams as in the tunnel-based solution. In parallel, Quentin De Coninck et al. proposed adding multipath capabilities as well as support for datagrams in the QUIC protocol [12]. These two solutions combine a congestion control scheme with the ability to carry datagrams. They could efficiently support non-TCP traffic and could serve as a starting point for future standards.

**IMPLEMENTATION AND DEPLOYMENT EXPERIENCE**

As explained in the previous section, the architecture proposed by the BBF for hybrid access networks relies on two components:

1. Hybrid aggregation gateway
2. A hybrid CPE

In this section, we describe our experience in implementing and deploying those two components and evaluate their performance.

**HYBRID CPE**

A HCPE is defined as a CPE that is attached to both an xDSL network and a 4G network. Most deployed xDSL and 4G CPEs use Linux. We have extended several of these with the open-source Multipath TCP implementation in the Linux kernel [13]. This stack completely supports Multipath TCP and is considered to be its reference implementation. We extend it with a transparent proxy that efficiently moves data from one Multipath TCP connection to one TCP connection and vice versa. These two features of Multipath TCP [13, 15]. The HCPE can be reused.

The maximum throughput that a HCPE can sustain mainly depends on the performance of its CPU. Older CPEs can reach a throughput of 100 Mb/s, while more recent ones such as most 4G gateways can reach much higher throughput. As an example, we evaluated the performance of a simple off-the-shelf CPE: the Linksys WRT1200AC. This CPE is equipped with a Marvell Armada 385 CPU clocked at 1.33 GHz. We attach a client running iPerf to this CPE and emulate the two access networks by using Gigabit Ethernet links with different delays: a 20 ms delay on one link to emulate the DSL network, and between 20 ms and 80 ms to emulate the LTE network. The difference of delay between the two links will have an impact on the reordering of the packets. We use iPerf to generate 10 downlink TCP connections that transfer data during 30 s. The baseline throughput for the setup on a Gigabit Ethernet link with 20 ms delay is 936 Mb/s, with a total CPU usage of 70 percent. Figure 4, in plain lines, the iPerf throughput measured on the client in function of the bandwidth available on both links, with a symmetric split 50 percent on each. The values of the maximum bandwidth on the X axis range from 1 Mb/s to 128 Mb/s converted in megabits per second, and have a maximum at 2 × 512 Mb/s, because the client is connected to the CPE with a Gigabit Ethernet link. Measurements are average over five iterations, and the standard deviation is indicated in black. Each line corresponds to a different delay on the emulated LTE link, while the delay for the emulated DSL is always 20 ms. It shows that the delay difference between the two links has no influence for throughputs below 576 Mb/s, but the aggregated speed decreases with an increasing difference. It also plots, by the dashed line, the average usage of one of the CPUs as a function of the available bandwidth. We can see that the CPU usage increases with the aggregated throughput, but a retail CPE can achieve up to 900 Mb/s by combining two 512 Mb/s links. The network operators who have contributed to the standardization of hybrid access networks [3, 4] have insisted on the ability to support specific policies such as specifying the ports or address blocks that can benefit from aggregation while also ensuring that the LTE network is only used when the DSL one is saturated. One key HCPE function is to decide when to create an LTE subflow based on:

- Operator objective to lower its costs
- User experience optimization, which is best when both networks are used

For subscribers, the experience depends on the available bandwidth, which is the combination of bandwidth from the xDSL and LTE networks. For the operator, the optimal business objective is to first use bandwidth from the least costly network (xDSL in the case considered here) and then use the minimum necessary bandwidth on the other network. The trade-off between these apparently mutually exclusive objectives is achieved by the overflow concept. The HCPE always starts to use the xDSL network until the available DSL capacity is fully used, and then overflows onto the LTE network. The overflow mode leverages two features of Multipath TCP [13, 15]. The HCPE continuously measures the load of the DSL link. If the average load is low, it does not attempt to
Thanks to the overflow mode, the HCPE first saturates the xDSL network before using the LTE one. This clearly shows that the hybrid access network utilizes both the xDSL link and what is available on the LTE link. The distribution between the DSL and LTE networks depends on the profiles of the users, the architecture initially proposed by BBF has been realized by leveraging new IETF protocols. We have described the key principles behind the tunnel-based and Multipath-TCP-based solutions. The first deployments combine DSL and LTE to provide higher bandwidth services in rural areas where the length of the copper pairs does not enable the deployment of faster DSL services such as VDSL2. Our measurements indicate that the Multipath TCP-based solutions, which can be deployed as software extensions on CPE routers and on commodity x86 servers, enable the use of the LTE network only once the DSL link becomes saturated while still supporting high-bandwidth services. The ongoing deployments demonstrate that network operators can optimize their assets by combining different access technologies to meet the demands of the end users.

**FIELD DEPLOYMENTS**

Several network operators have started to deploy hybrid access networks using the Multipath TCP solutions described in this article. Their main use case is to provide faster Internet access services in rural areas where the length of the twisted pair lines does not allow the xDSL technologies to reach more than a few megabits per second. The customer surveys they have conducted indicate that these hybrid access networks improve the quality of experience perceived by the end users.

As an illustration, Fig. 6 provides some of the statistics collected on one HAG deployed in a European network. This HAG uses the implicit mode and serves about 10,000 homes. This HAG is running on a server equipped with Intel Xeon-Platinum 8180 (2.5 GHz/28-core/205 W) and four Mellanox ConnectX-4 10 Gb/s interfaces. The four interfaces are combined in a 40 Gb/s link aggregation group (LAG) and divided into three virtual local area networks (VLANs): one attached to the DSL network, one to the LTE network and one to the Internet through a backbone router.

**CONCLUSION**

During the last few years, hybrid access networks have matured. The architecture initially proposed by BBF has been realized by leveraging new IETF protocols. We have described the key principles behind the tunnel-based and Multipath-TCP-based solutions. The first deployments combine DSL and LTE to provide higher bandwidth services in rural areas where the length of the copper pairs does not enable the deployment of faster DSL services such as VDSL2. Our measurements indicate that the Multipath TCP-based solutions, which can be deployed as software extensions on CPE routers and on commodity x86 servers, enable the use of the LTE network only once the DSL link becomes saturated while still supporting high-bandwidth services. The ongoing deployments demonstrate that network operators can optimize their assets by combining different access technologies to meet the demands of the end users.
Combining different heterogeneous access networks to provide faster, cheaper, and more resilient services to their customers. Although the first hybrid access networks combined xDSL and LTE, the technology is generic and can be applied to any type of network. Recently, the 3rd Generation Partnership Project has decided to also reuse the 0-RTT Convert Protocol to support the access traffic steering, switch, and splitting that will enable 5G networks to combine 5G with other technologies such as Wi-Fi and satellite.

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References
[1] IHS Markit Ltd., “Point Topic,” Broadband Coverage in Europe, 2018; http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=52968, accessed 26 Mar. 2019. DOI: 10.2759/358688
[2] FCC, 2018 Broadband Deployment Report; https://www.fcc.gov/reports-research/reports/broadband-progress-reports/2018-broadband-deployment-report, accessed 1 Apr. 2019.
[3] BBF, TR-348 Hybrid Access Broadband Network Architecture, issue 1, Aug. 2016.
[4] BBF, TR-378 Nodal Requirements for Hybrid Access Broadband Networks, issue 1, May 2019.
[5] M. Amend et al., “TCP Extensions for Multipath Operation with Multiple Addresses,” IETF RFC 6824, Jan. 2013.
[6] N. Leymann et al., “Huawei’s GRE Tunnel Bonding Protocol,” IETF RFC 8157, May 2017.
[7] O. Bonaventure et al., “0-RTT TCP Convert Protocol,” Internet draft, draft-ietf-tcpm-converters-06, work in progress, Mar. 2019.
[8] N. Leymann, “Hybrid Access Deployment # DT,” Banana Bof, IETF95, Buenos Aires, Argentina, Apr. 2016.
[9] C. Raiciu et al., “How Hard Can It Be? Designing and Implementing a Deployable Multipath TCP,” Proc. 9th USENIX Conf. Networked Systems Design and Implementation, 2012.
[10] O. Bonaventure and S. Seo, “Multipath TCP Deployments,” IETF J., Nov. 2016.
[11] M. Amend et al., “A Framework for Multaccess Support for Liveliable Internet Traffic Using Multipath DCCP,” IEEE ICN ’19, Osnabruck, Germany, 2019.
[12] Q. De Coninck et al., “Pluginizing QUIC,” Proc. ACM Special Interest Group on Data Communication, 2019.
[13] C. Paasch et al., “Multipath TCP in the Linux Kernel”; https://www.multipath-tcp.org, accessed 26 Mar. 2019.
[14] C. Paasch, and O. Bonaventure, “Multipath in the MiddleBox,” HotMiddlebox ’13, Santa Barbara, CA, 2013.
[15] C. Paasch et al., “Experimental Evaluation of Multipath TCP Schedulers,” Proc. 2014 ACM SIGCOMM Wksp. Capacity Sharing Wksp., 2014, pp. 27–32.

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