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LTE Wi-Fi Aggregation—Assessing OTT Solutions

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Executive Summary

Wireless operators have always been driven to meet increasing user demand by achieving higher data rates and improving quality of service. They have used different types of carrier aggregation to fulfill this need, including several commonly used industry-standard solutions, such as

- traditional carrier aggregation,
- aggregation of carriers in either licensed or unlicensed spectrum by using a single technology like LTE, or
- aggregation of carriers by using LTE in licensed spectrum and Wi-Fi in unlicensed spectrum.

Each aggregation solution has benefits that offer higher date rates, improved quality of service, more efficient spectrum utilization, and enhanced user experience. However, these benefits need to be weighed against certain tradeoffs in terms of capital investments, deployment complexities, and spectrum and network infrastructure ownership. These tradeoffs might create barriers for Multiple Service Operators (MSOs) that do not have cellular infrastructure.

Over-the-top (OTT) aggregation is an alternative to industry-standard aggregation solutions; it can be implemented by MSOs irrespective of the cellular network assets they own. The performance of OTT aggregation solutions from four vendors was tested and validated. During testing, the end-user device was located in overlapping LTE and Wi-Fi network coverage; testing covered use of either network without OTT aggregation and use of both networks simultaneously with OTT aggregation. The test results indicated increased throughput and improved user experience with OTT aggregation. (See the Conclusion section for a summary of the benefits of OTT aggregation shown by the test results.)

The key advantages of OTT aggregation solutions over other aggregation solutions include the following:

- high data rates with minimal tunneling overhead and no changes to the existing LTE and Wi-Fi networks,
- gapless handovers with Internet Protocol (IP) continuity,
- ability to set customized policies and manage QoS (Quality of Service) without needing access to Mobile Network Operators' (MNOs) Evolved Packet Core (EPC), and
- ability to aggregate an MSO-owned Wi-Fi network with third-party (private) Citizen's Band Radio Service (CBRS) networks.

Introduction

In order to satisfy the insatiable demand1 for high-throughput user applications such as high definition videos, videoconferencing, and interactive gaming, wireless operators are exploring techniques to add network capacity and enhance their service offering. Aggregation is one way to achieve those goals.

Aggregation works by combining smaller blocks of spectrum to provide a single virtual channel whose bandwidth is the sum of them all. It can benefit wireless operators by adding capacity, boosting throughput, and increasing bandwidth, thereby enhancing network performance and improving the quality of the user experience. Many wireless operators are now exploring ways to implement different industry-standard forms of aggregation.

For example, with the introduction of 3GPP Release 8 commercial LTE network deployments, MNOs have taken advantage of carrier aggregation in licensed spectrum to increase network capacity and enhance coverage. They have continued to use this form of carrier aggregation in unlicensed spectrum because it is available at no additional cost. In dense market areas, MNOs have deployed LAA and LTE-U, which use carrier aggregation in licensed and unlicensed spectrum, to increase data rates and provide enhanced user experience.2

Additional 3GPP channel aggregation solutions, such as LTE WLAN Aggregation (LWA) and LTE WLAN Aggregation using IPSec Tunnel (LWIP), provide similar benefits of increased data rate and enhanced user experience. However, to use these standard solutions, the wireless operator needs to either own spectrum and cellular infrastructure or have MVNO agreements with operators who own those assets. These standard aggregation solutions also require upgrades to either hardware or software to support new chipsets, interfaces, nodes, or protocols, which incurs increases to capital expenditures (CapEx) and operating expenses (OpEx).

Each aggregation method has its own benefits and tradeoffs and will present different challenges to MSOs implementing these industry-standard aggregation methods.

Over-the-top (OTT) aggregation, on the other hand, is an alternate solution to industry-standard aggregation solutions. OTT aggregation solutions leverage existing cellular and Wi-Fi infrastructures without requiring any significant changes to the network or end-user devices. Thus, the OTT aggregation solution allows MSOs to provide high data rates and improved user experience in an economical way.

This technical brief will give an overview of the traditional, industry-standard aggregation solutions; a detailed description of OTT aggregation solutions and how they compare to the standard options; and an overview of testing conducted by CableLabs to validate the benefits of aggregation solutions on end-user throughput and quality of experience (QoE).

Standardized Aggregation Solutions

MNOs predominantly use carrier aggregation (CA) to utilize the spectrum efficiently, boost data rates, and increase network capacity. The CA feature, part of LTE- Advanced defined in 3GPP Release 10, enables operators to combine multiple LTE component carriers (CCs), each up to 20 MHz wide, to create wider bandwidth services. In a similar way, MSOs utilize channel bonding in Wi-Fi to increase the channel bandwidth of Wi-Fi channels, thus providing increased data rates to the end user.

Besides traditional carrier aggregation (LTE aggregating multiple channels in licensed bands) and channel bonding (Wi-Fi aggregating multiple channels in unlicensed bands), there are other aggregation solutions.

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[1] "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021 White Paper," March 2017, Cisco
[2] "AT&T Secure in Decision to Go with LAA and Skip LTE-U," July 2017, Fierce Wireless—Monica Alleven;
"Verizon Confirms Shift to LAA over LTE-U," November 2017, Mobile World Live—Diana Goovaerts;
"Sprint Enters LAA Race," December 2017, Mobile World Live—Diana Goovaerts

- Aggregation of carriers in either licensed or unlicensed spectrum by using a single technology like LTE
    - LTE Unlicensed (LTE-U), standardized by LTE-U Forum
    - License Assisted Access (LAA), standardized by 3GPP
- Aggregation of carriers by using both LTE in licensed spectrum and Wi-Fi in unlicensed spectrum
    - LTE WLAN Aggregation (LWA), standardized by 3GPP
    - LTE WLAN Aggregation using IPSec Tunnel (LWIP), standardized by 3GPP
- Use of Multipath TCP (MPTCP) to aggregate LTE and Wi-Fi by using multiple simultaneous TCP links to transmit data

LTE-U and LAA operate LTE technology in both licensed and unlicensed spectrum. They use carrier aggregation by using the primary LTE carrier as an anchor in licensed spectrum while aggregated with the secondary LTE carrier, or the supplemental downlink carrier, in the unlicensed spectrum. The supplemental downlink carrier uses 5G Hz, UNII-1 and UNII-3 bands. Release 14 enhanced LAA (eLAA) allows the carrier in unlicensed spectrum to be used in both uplink and downlink. LTE-U and LAA do not utilize existing Wi-Fi infrastructure, so they only benefit MSOs that have an existing LTE infrastructure.

Aggregation using LWA and LWIP converges both LTE and Wi-Fi networks and resolves the coexistence problems associated with LTE-U and LAA (i.e., LTE and Wi-Fi trying to access the unlicensed spectrum). LWA and LWIP leverage both LTE and Wi-Fi infrastructures, with LTE operating in the licensed spectrum and Wi-Fi operating in the unlicensed spectrum. Integration of LTE and Wi-Fi occurs at the Packet Data Convergence Protocol (PDCP) layer with LWA and at the Internet Protocol (IP) layer with LWIP. Although LWA requires upgrades to Wi-Fi infrastructure, the LWIP solution is agnostic to Wi-Fi infrastructure. LWIP is designed to work over legacy Wi-Fi infrastructure without requiring any specific changes.

MPTCP is a proxy-based LTE and Wi-Fi aggregation solution defined by the Internet Engineering Task Force (IETF). Integration of LTE and Wi-Fi occurs at the Transmission Control Protocol (TCP) level rather than at the radio link level as in 3GPP-defined LWA solutions. MPTCP is an extension of traditional TCP; the only difference is that MPTCP uses multiple paths to send the data concurrently, whereas traditional TCP uses a single path between the client and the server. MPTCP, although an attractive solution, has not been widely adopted by MNOs because of the slow standardization process and some implementation concerns. Standardization for MPTCP is in motion, but the architecture and deployment details for MPTCP proxy-based aggregation have not yet been specified.

Despite the benefits of these aggregation solutions, they present barriers to implementation for some carriers:

- wireless operators that do not own a licensed spectrum and a cellular infrastructure,
- small operators that do not own large blocks of spectrum or an established cellular infrastructure, and
- operators that cannot afford high-capital investments to deploy new RAN (radio access network) equipment to support the aggregation technologies and associated spectrum.

Alternate Aggregation Solution—OTT Aggregation

The over-the-top (OTT) aggregation solution leverages the inherently separate interfaces for LTE and Wi-Fi on mobile devices. OTT solutions enable simultaneous data communication on both interfaces by creating an IPSec tunnel between the embedded OTT aggregation application on a mobile device and an OTT aggregation server hosted in the cloud or locally on a virtual machine.

Network Architecture

The network architecture for OTT aggregation (Figure 1) creates a tunnel between (1) an aggregation server or aggregation gateway and (2) a mobile client application on the user's device. The server is connected to the backhaul network, WLAN controller, and LTE EPC in the downlink (DL) direction and segregates traffic on both LTE and Wi-Fi links based on configurable policies. The user equipment (UE) will receive the requested DL data from both LTE and Wi-Fi networks simultaneously (thereby enhancing the user experience and data rates), and the mobile client application will combine the previously segregated data at the UE. In the uplink (UL) direction, the mobile client application will segregate the data on both LTE and Wi-Fi links, and the aggregation server will then combine the data to the original state.

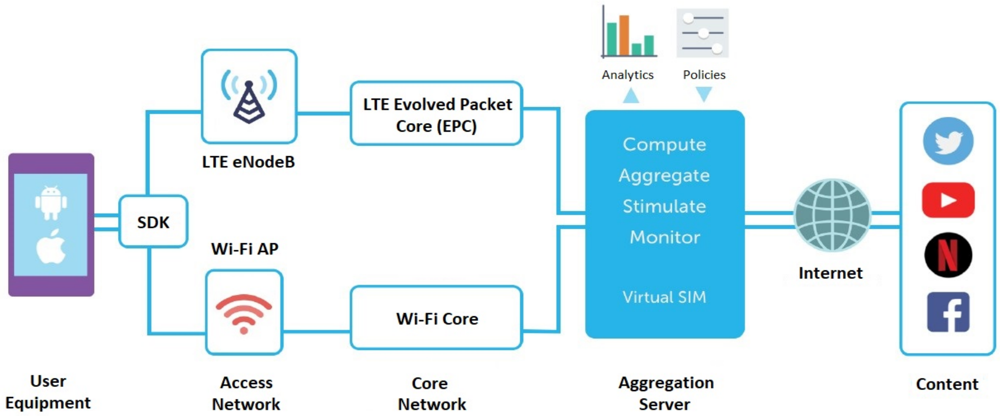

Figure 1. LTE–Wi-Fi Aggregation Using OTT Aggregation

The mobile client application virtualizes the hardware and software components of the mobile device and exposes a multipath data plane in the form of a tunnel. When active, the client application securely establishes multipath connections over all available network interfaces. It can be installed directly onto the end devices (downloaded from the Apple store or Google Play) and does not require any new hardware or additional changes to end devices.

Most OTT solutions offer customized network policies that can be configured on the aggregation server to support optimal user experience and maximum offload to reduce costs. The aggregation server also includes an interactive graphical user interface (GUI) that offers real-time insights on and control over the service provider’s networks through administration tools for system health, network alerts, notifications, and analytics. Each traffic sub-flow through the aggregation server is monitored in real-time for specific key performance indicators (KPIs) that indicate sub-flow health and quality; the server measures parameters such as sub-flow throughputs, estimated bandwidths, packet loss, and latency.

Operational Modes

MSOs can use the OTT aggregation solution for varied use cases:

- Maximum throughput mode—Allow users to get aggregated maximum throughput from both LTE and Wi-Fi links.
- Target throughput mode—Use the Wi-Fi link if the requested throughput is below the maximum Wi-Fi link throughput and use the LTE link for the “spillover” throughput if the requested throughput exceeds the maximum Wi-Fi link throughput.
- Gapless handover mode—Provide a smooth transition without any service disruption when the user moves between LTE and Wi-Fi networks by performing packet replication on both networks.
- Redundancy mode—Provide a robust network, in case of high-latency or packet-loss environments, by transmitting the same packets over both LTE and Wi-Fi networks.

Each mode targets different applications and use cases that can be dynamically controlled based on location and network conditions. The user will gain different advantages from each mode, so with dynamic mode selection, overall user experience will be enhanced.

Key Features and Benefits for MSOs

Key features of OTT aggregation solutions:

- Faster deployment without the need to modify existing LTE and Wi-Fi infrastructures
- High data rates by using both LTE and Wi-Fi networks simultaneously
- Gapless handovers when moving from locations with either LTE or Wi-Fi access to locations with access to both and vice versa by duplicating packets on both interfaces
- Lower operating costs supported by IP continuity and bandwidth aggregation across all heterogeneous networks without access to LTE EPCs (makes OTT aggregation an attractive solution for both light and full MVNOs)

Other benefits of OTT aggregation solutions:

- Designed to have minimal overhead with real-time control for proactive network testing, bridging multiple networks, and routing in multi-hop, mesh, or multicast scenarios
- Ability to perform content-based, location-based, and SSID-based aggregation; support roaming between multiple operators; and support work through VPNs of enterprise Wi-Fi networks
- Ability to switch between the available networks in real time, when the user is mobile, thereby aggregating at all times based on policies set by the operator
- Ability to perform both packet-based and flow-based aggregation

Key benefits to MSOs:

- Aggressive offload of traffic to less expensive connections while maintaining a high Quality of Experience (QoE) for end users
- Aggregation of MSO-owned CBRS network and Wi-Fi network

Analysis of OTT Aggregation Against Other Aggregation Methods

Each aggregation solution has its own benefits and tradeoffs and will present different challenges to the MSOs implementing them, based on the assets they own. However, before an MSO deploys OTT aggregation solutions, it is important for the MSO to understand how they perform against the other traditional aggregation technologies.

Infrastructure Requirements

Standardized Aggregation Solutions	OTT Aggregation
LTE-U, LAA, LWA, LWIP—MSOs must own a licensed spectrum and a cellular infrastructure or have an agreement with an operator who owns an LTE infrastructure.	MSOs that own both or either infrastructures can deploy without needing any agreements with an operator who owns a cellular network.

LTE and Wi-Fi Coexistence

Standardized Aggregation Solutions	OTT Aggregation
LTE-U—Can only be implemented in markets where Listen Before Talk (LBT) is not mandated in the unlicensed spectrum.	Operates in LTE licensed bands and Wi-Fi unlicensed bands, so there is no concern about coexistence.
LAA—Uses method similar to LBT to avoid interference and attempt fair coexistence with Wi-Fi. However, LBT-like implementation in LAA does not guarantee fair coexistence because of significant differences between 3GPP-defined and Wi-Fi LBT implementations.	

Need for New Network Elements, Interfaces, and Protocols

Standardized Aggregation Solutions	OTT Aggregation
LTE-U, LAA—New radio access network (RAN) hardware, which requires significant increases in time and capital investment.	Works on existing protocols. Requires an OTT aggregation server (agnostic to LTE and Wi-Fi infrastructures) and a client application embedded on the end-user equipment.
LWA—Software upgrades to support new interfaces and messages.	
LWIP—Introduces new network elements, such as LWIP Security Gateway.	
MPTCP—MPTCP-enabled clients and an MPTCP proxy server.	

End-Device Support

Standardized Aggregation Solutions	OTT Aggregation
LTE-U, LAA—End-user equipment must have new chipsets to support specific bands.	Agnostic to end-user equipment, so no hardware requirements or software upgrades are needed.
LWA—Devices must support new protocols and information elements.	
MPTCP—Software upgrades are required on existing client devices to support multiple simultaneous TCP connections.	

Cost-Effectiveness

Standardized Aggregation Solutions	OTT Aggregation
LTE-U, LAA—New access equipment increases CapEx; replacing existing access network equipment increases OpEx.	Economical to implement because no changes to existing LTE and Wi-Fi network infrastructures are required.
LWA, LWIP—Pushing new software load onto existing access network equipment (to support new network nodes, interfaces, protocols, and messaging) increases OpEx.	

OTT Aggregation Testing

CableLabs conducted six tests with four vendors to validate the performance of OTT aggregation solutions. The test cases used the four operating modes described earlier with OTT aggregation enabled. They measure the following OTT features, which are expected to provide performance improvements beneficial to MSOs:

- aggregated throughput with single and multiple clients,
- consistent throughput maintained during Wi-Fi network degradation, and
- lowered packet loss and data session continuity during network transition.

Test Equipment and Setup

Figure 2 shows the lab setup for the OTT aggregation testing.

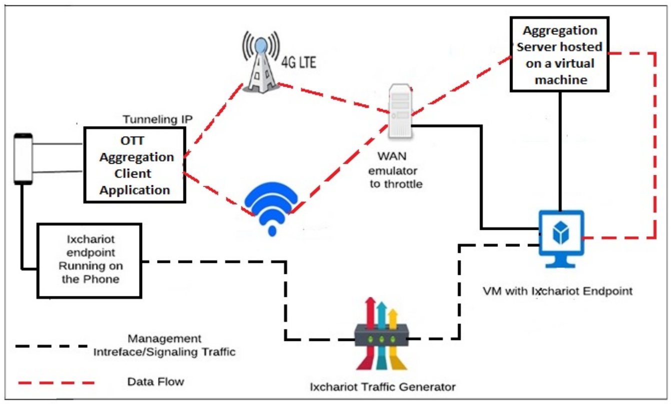

Figure 2. OTT Aggregation Lab Setup

The following test equipment was used:

- End-User Device: Android phone with OTT client application
- Network Emulator: replicates real-world network issues such as latency, bandwidth control (i.e. throttling), and frame drops on user traffic in a controlled environment
- Traffic Generator: IxChariot; simulates application traffic across multiple clients, generates TCP flows with maximum and limited bandwidths, and records application layer throughput (captured on IxChariot)
- LTE eNodeB: provides cellular coverage using TDD Band 41 with 20 MHz bandwidth, 64QAM, 2x2 MIMO, and a TDD configuration with DL:UL ratio of 80:20 with a theoretical data rate of 150 Mbps and practical data rate of 120 Mbps
- Wi-Fi AP: operates on channel 36 in 5 GHz band at 80 MHz bandwidth using 11ac, 2x2 MIMO to provide Wi-Fi coverage (adjacent channel interference test case used channel 40 and a 20 MHz bandwidth)
- OTT Aggregation Server: locally hosted on a virtual machine

For testing purposes, the LTE link was throttled to 50 Mbps, and the Wi-Fi link was throttled to 100 Mbps for some test cases and to 50 Mbps for others.

Test Cases, Results, and Observations

Test Case 1: Baseline Characterization

Test case 1 evaluates the baseline performance of LTE and Wi-Fi networks by capturing the maximum TCP throughput obtained separately on a 50 Mbps LTE link and a 100Mbps Wi-Fi link with aggregation disabled and enabled. The expected result was to observe minimum deviation in throughput values with and without aggregation enabled, indicating low throughput loss caused by tunneling overhead of the OTT aggregation solution.

Table 1 represents average throughput values for 10 runs, each of 120 sec duration, delivering the maximum throughput by using IxChariot with 50 Mbps on the LTE link and 100 Mbps on the Wi-Fi link. The LTE and Wi-Fi throughput values for all vendors show minimal deviation with aggregation enabled or disabled and indicate low tunneling and encryption overhead (5–10%) caused by the OTT aggregation solutions.

Table 1. Throughput Captured on IxChariot, With and Without Aggregation

		Throughput (Mbps)			
Network	**Aggregation**	**Vendor 1**	**Vendor 2**	**Vendor 3**	**Vendor 4**
LTE (50 Mbps link)	Disabled	45	46	49	46.3
	Enabled	44	44.5	49	44.5
Wi-Fi (100 Mbps link)	Disabled	95	99.6	94	95
	Enabled	91	99.3	90.6	94.8

Test Case 2: Aggregation Characterization in Maximum Throughput Mode

Test case 2 evaluates the performance of OTT aggregation in the maximum throughput mode when an end-user device is connected to both LTE and Wi-Fi networks simultaneously in overlapping coverage. The traffic generator was configured to deliver 50 Mbps thoughput to the end device with a 50 Mbps LTE link and a 100 Mbps Wi-Fi link, as described in test case 1. With aggregation enabled and the end device operating in maximum throughput mode, the user will receive aggregated throughput utilizing both networks rather than a single network.

As shown in Figure 3, both the LTE eNodeB and the Wi-Fi AP were collocated, providing overlapping coverage to the end-user device placed at the cell center. The RSRP recorded on the end user device was -60 dbm.

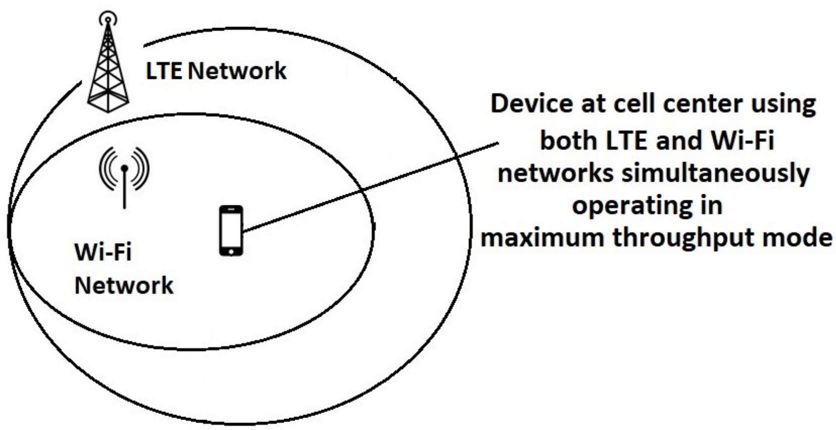

Figure 3. Aggregation Characterization in Maximum Throughput Mode

Table 2 provides results of the maximum aggregated downlink throughput values captured on IxChariot for 10 runs, each of 120 sec duration. The average maximum aggregated throughput for the four vendors is approx. 135 Mbps. According to the baseline results of test case 1, an aggregated throughput of 140 Mbps would be expected (i.e., about 95 Mbps on Wi-Fi and about 45 Mbps on LTE). However, the average measured throughput of approx. 135 Mbps is due to a 10–15 % loss at the application layer resulting from tunneling overhead and encryption introduced by the implementation of the OTT aggregation solution. The OTT aggregation takes an average of 5–6 seconds to trigger and reach the targeted aggregation throughput levels.

Table 2. Aggregated Downlink Throughput Captured on IxChariot

	Throughput (Mbps)			
Network(s) Used	**Vendor 1**	**Vendor 2**	**Vendor 3**	**Vendor 4**
Aggregated LTE and Wi-Fi (LTE link: 50 Mbps; Wi-Fi link: 100 Mbps)	130.8	138.41	135	138.14

MSO benefit: OTT aggregation in maximum throughput mode delivers higher data rates by utilizing LTE and Wi-Fi networks simultaneously.

Test Case 3: Link Characterization in Target Throughput Mode

Test case 3 evaluates OTT aggregation performance when using a Wi-Fi network to achieve target throughput and using an LTE network for “spillover” throughput. The test setup described in test case 2 and figure 3 are also used in this test case. The aggregation was enabled by using the OTT aggregation client on the device with the solution operating in target throughput mode. The expected result was to obtain consistent throughput with a degraded Wi-Fi network when using the OTT aggregation solution.

Figure 4 shows the average thoughput at the application layer (on IxChariot) for a representative vendor. The traffic generator was configured to deliver 50 Mbps thoughput to the end device with a 50 Mbps LTE and Wi-Fi link for a total of 10 runs, each of 120 sec duration. During the test run, the Wi-Fi throughput was throttled from 50 to 6 Mbps, but the application layer shows a constant throughput maintained close to 50 Mbps. A small dip in throughput from 50 to 22 Mbps is observed when the throttling was initiated.

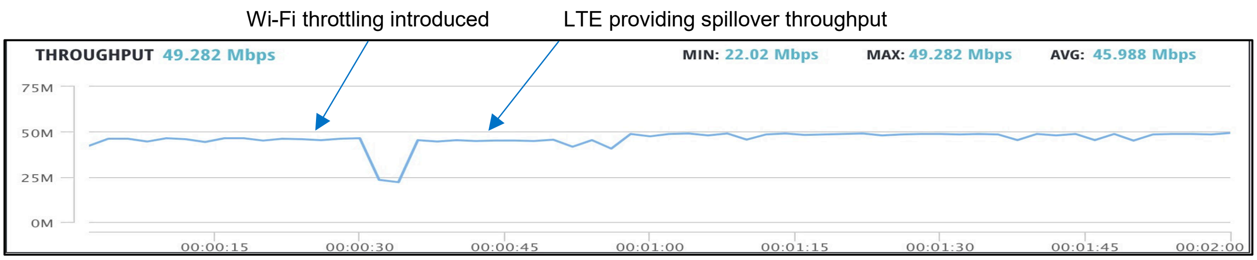

Figure 4. Application Layer Downlink Throughput Captured on IxChariot

Figure 5 shows the Wireshark capture on the switch collected simultaneously to show the independent usage of Wi-Fi and LTE links. The device initially uses only the Wi-Fi link to achieve the target throughput, but when the Wi-Fi link is throttled, and the device is unable to achieve the target throughput, the device starts using the LTE link. The Wireshark capture shows no throughput for first 8–10 sec, accounted for by the delay between starting the Wireshark capture on the switch and starting the test on IxChariot.

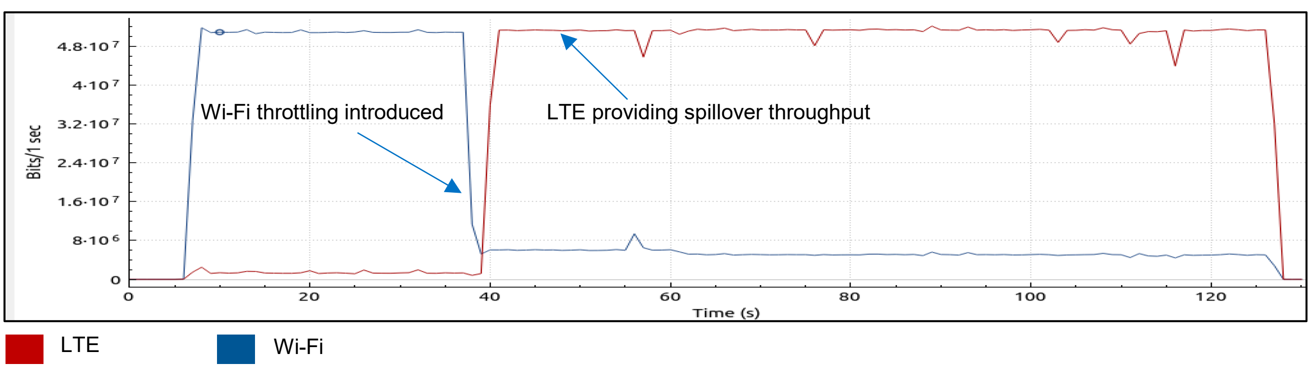

Figure 5. Wireshark Capture on the Switch

MSO benefit: OTT aggregation in target throughput mode provides a constant throughput level, borrowing spillover throughput from the LTE link when the Wi-Fi network is degraded. Use of the Wi-Fi link primarily in good network conditions can increase revenue.

Test Case 4: Mobility Testing with Gapless Handover Feature

Test case 4 evaluates network performance with the OTT aggregation solution when a device transitions between LTE and Wi-Fi networks. The expected result was to observe a seamless user experience with no dropped calls and no noticeable service disruption as the result of using the gapless handover feature of OTT aggregation to provide traffic redundancy.

As shown in Figure 6, the performance of OTT aggregation solutions for mobility was tested for both non-collocated and collocated scenarios. The gapless handover feature was tested for 10 runs in both directions (LTE to Wi-Fi and Wi-Fi to LTE), each of 120 sec duration, with the SIP video-calling application sending RTP traffic. The solutions from multiple vendors showed consistent results of less than 5–10% packet loss with no noticeable service disruptions or dropped calls, even with an RSRP of -125 dBm at cell edge of LTE network and RSSI of -84 dbm at cell edge of Wi-Fi network. Without the OTT aggregation solution, packet loss was significantly higher, approx. 20–25% with noticeable service disruption of 6–8 sec, with similar RSRP and RSSI levels at the cell edge of both networks. One of the vendors had implementation issues with the SIP call not resuming on the Wi-Fi network when moving from LTE to Wi-Fi-only coverage.

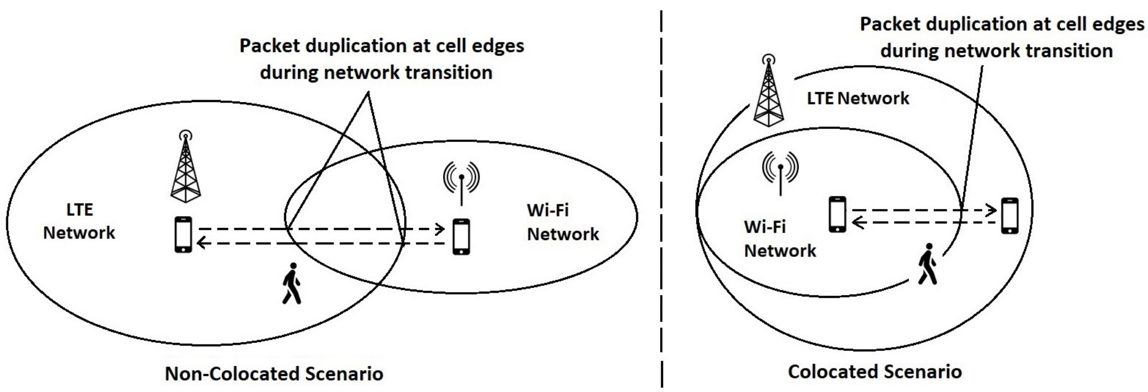

Figure 6. Mobility with LTE–Wi-Fi Aggregation with Gapless Handover

MSO benefit: OTT aggregation enhances the user experience at cell edges during network transitions to and from Wi-Fi networks by duplicating packets and maintaining the data session without any noticeable disruption in service.

Test case 5 evaluates the performance of OTT aggregation when the devices under test experience interference from neighboring Wi-Fi APs operating in the adjacent channel. The expected result was to obtain a consistent throughput in an environment with high interference by using the OTT aggregation solution.

As shown in Figure 7, the device under test is connected to an LTE network and a Wi-Fi network, providing a means for aggregation. Two neighboring Wi-Fi APs, each with a connected device, are operating in the adjacent channel.

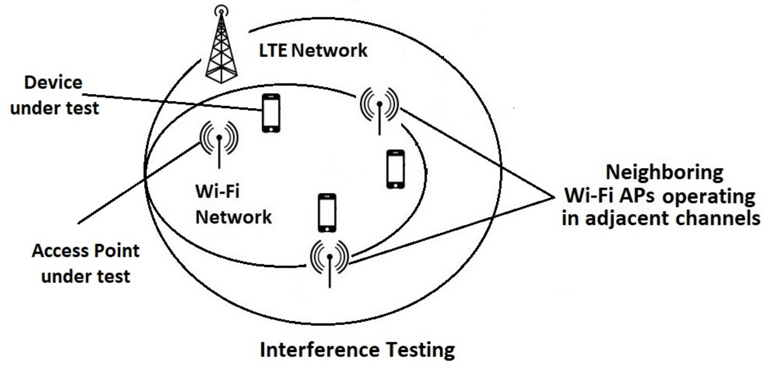

Figure 7. Adjacent Channel Interference on a Wi-Fi Network

Performance under interference both with and without aggregation was tested for 10 runs, each of 60 sec duration, delivering 50 Mbps TCP throughput by using IxChariot with 50 Mbps on the Wi-Fi and LTE links. Figure 8 shows the network performance without the OTT aggregation solution. As soon as the adjacent channel interference at 20 Mbps is initiated from the neighboring APs, the Wi-Fi throughput is degraded for the device under test from 50 to 30 Mbps.

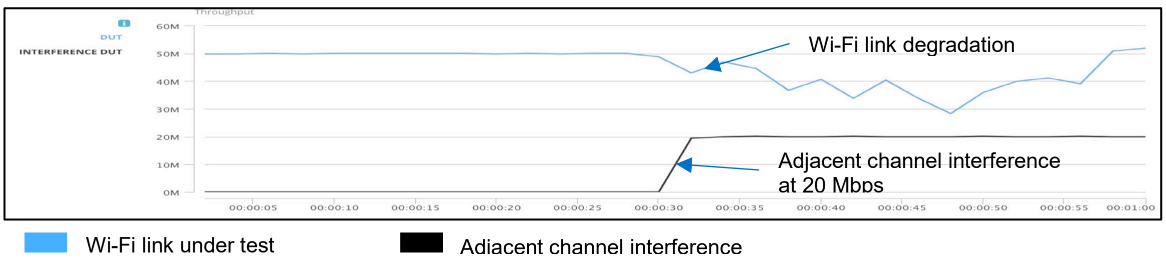

Figure 8. Application Layer Throughput Captured on IxChariot with ACI at 20 Mbps

Figure 9 shows the network performance with the OTT aggregation solution enabled in target throughput mode. As soon as the adjacent channel interference is initiated from the neighboring APs, the Wi-Fi throughput is degraded, but the overall aggregated throughput is maintained at 50 Mbps by borrowing the "spillover" throughput from the LTE link. The adjacent channel interferer is 8–10 dB stronger than the AP-STA pair under test.

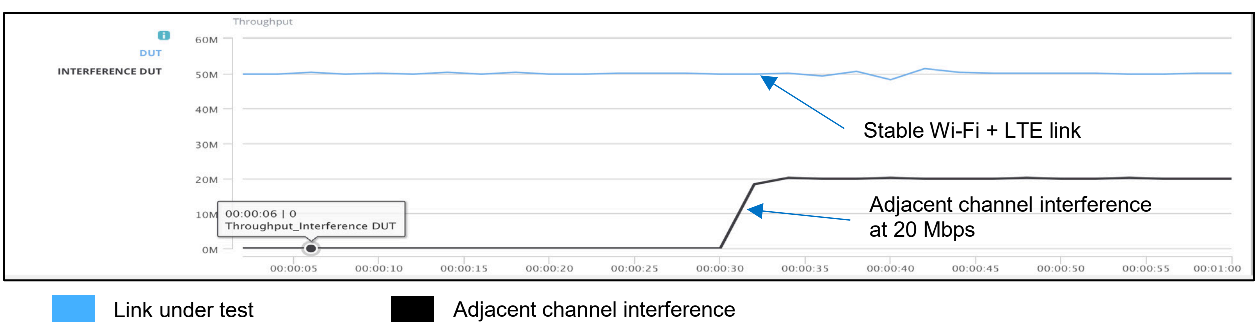

Figure 9. Application Layer Throughput Captured on IxChariot with ACI at 20 Mbps and Aggregation Enabled

MSO benefit: OTT aggregation enhances user experience by delivering consistent throughput even in a high-interference environment.

Test Case 6: Multiple Client Performance

Test case 6 evaluates the performance of OTT aggregation solutions with multiple users requesting high traffic on both LTE and Wi-Fi networks. The expected result was to observe higher throughputs with OTT aggregation enabled.

As shown in Figure 10, multiple clients located at cell center, cell middle, and cell edge are connected to both LTE and Wi-Fi networks and are requesting high traffic. The performance of each device at different locations within the network coverage was evaluated for 10 runs, each of 60 sec duration, pushing 50 Mbps TCP throughput by using IxChariot with 50 Mbps on the Wi-Fi and LTE links.

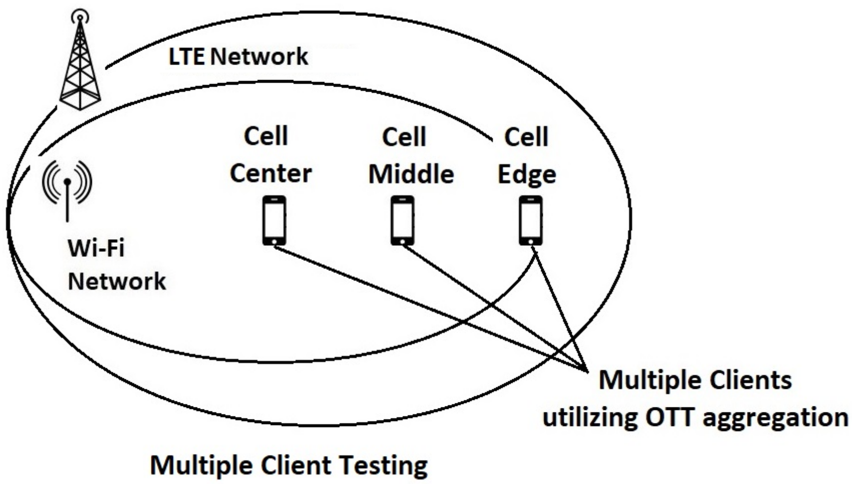

Figure 10. Multiple Client Performance

Figure 11 shows application layer throughput collected on IxChariot for all the clients. High-throughput fluctuations were observed for all the clients. None of the clients were able to maintain a consistent 50 Mbps throughput but were able to maintain an average throughput of at least 20 Mbps. Without OTT aggregation, the clients were unable to maintain even 10 Mbps average throughput. The devices located at cell center and cell middle had more inclination towards using the Wi-Fi network, and the device located at cell edge had more inclination towards using the LTE network to achieve the desired throughput. The results indicated that the throughput with OTT aggregation was better than the throughput without OTT aggregation.

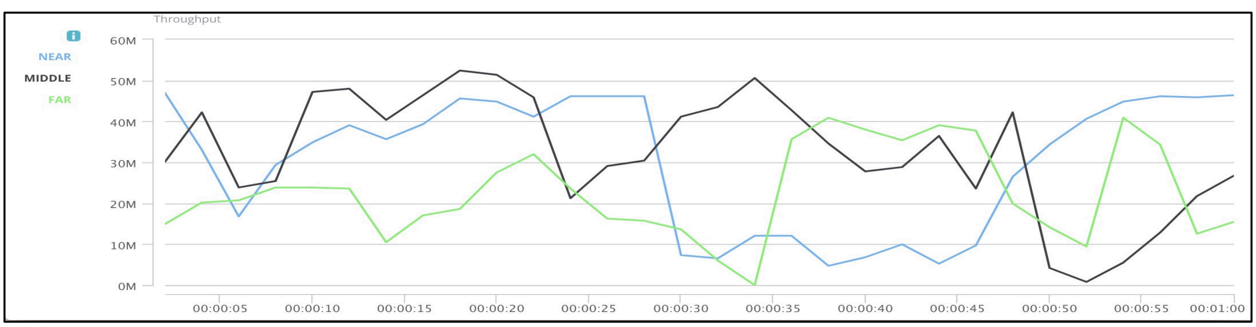

Figure 11. Application Layer Throughput Captured on IxChariot for All Clients with Aggregation Enabled

MSO benefit: OTT aggregation enhances the user experience by supporting higher throughput levels even when the Wi-Fi network is congested. In extreme congestion, the redundancy mode uses traffic duplication to avoid dropped calls and noticeable disruptions.

Conclusion

Without Aggregation	With OTT Aggregation
Increased throughput using 50 Mbps LTE link and 100 Mbps Wi-Fi link	
Average throughput of 95 Mbps using only Wi-Fi link or 45 Mbps using only LTE link	Average aggregated throughput of 135 Mbps using LTE and Wi-Fi simultaneously with 5–10% of tunneling and encryption overhead
Maintaining throughput with Wi-Fi network degradation using 50 Mbps LTE and Wi-Fi link	
60% throughput degradation	50 Mbps throughput maintained
Without Wi-Fi degradation: 50 Mbps on Wi-Fi	Without Wi-Fi degradation: 50 Mbps on Wi-Fi
With Wi-Fi degradation: 30 Mbps on Wi-Fi	With Wi-Fi degradation: 30 Mbps on Wi-Fi, 20 Mbps on LTE
Mobility performance between LTE and Wi-Fi with active data session	
25–30% packet loss	5–10% packet loss
Loss of data session	No loss of data session
5–6 sec of noticeable disruptions	No noticeable disruptions
Multiple client performance using 50 Mbps LTE and Wi-Fi link	
Average throughput using Wi-Fi link only:	Average throughput using LTE and Wi-Fi link:
30 Mbps at cell center (40% degradation)	45 Mbps at cell center (10% degradation)
15 Mbps at cell middle (70% degradation)	30 Mbps at cell middle (40% degradation)
5 Mbps at cell edge (90% degradation)	20 Mbps at cell edge (60% degradation)

Carrier aggregation can help meet increasing user demand by facilitating higher data rates and improving quality of service. This technical brief has analyzed several available aggregation solutions and discussed the benefits and tradeoffs for each.

Solutions like LAA and LTE-U increase network performance by aggregating unlicensed and licensed spectrum, but deployments of these solutions increase CapEx by requiring new radio access equipment and device support. Additionally, Wi-Fi operators may consider LTE-U problematic, given its weak and ill-defined coexistence requirements, and prefer LAA for its more suitable coexistence requirements. Any flavor of LTE operating in an unlicensed band—i.e., LTE-U or LAA—will affect Wi-Fi network performance; increased traffic on current Wi-Fi channels will reduce airtime and spectrum availability. LTE-U and LAA are already being deployed in heavily congested areas.

LTE solutions like LWA and LWIP aggregate a Wi-Fi carrier at the 5 GHz band with an LTE carrier as an anchor in licensed spectrum and thereby guarantee fair coexistence. Implementation of LWA and LWIP, however, requires MNOs to deploy new compatible access networks, utilize existing Wi-Fi networks, and enter into agreements with MSOs if they do not own the Wi-Fi network themselves, all of which affects the revenue of the business. LWA introduces new interfaces between a Wi-Fi AP and an LTE eNodeB, requiring an upgrade of Wi-Fi infrastructure, and LWIP introduces new network elements like LWIP SecGW. For these reasons, MNOs may not consider LWA and LWIP attractive aggregation solutions.

An MSO considering LWA and LWIP would need to either own a licensed spectrum and an LTE network or have a MVNO agreement with MNOs. With a MVNO agreement, an MSO cannot control the policies for the MSO subscribers when they are on the MNO's network. Further, LWA does not allow end devices to aggregate licensed spectrum with unlicensed spectrum from third-party networks, which reduces the opportunities for offloading traffic and excludes connections to widespread and growing networks such as Wi-Fi and 3.5 GHz networks.

Lastly, MPTCP is yet to be standardized for LTE and Wi-Fi aggregation and has implementation concerns regarding the alignment of operator policies on both LTE and Wi-Fi networks and the need for client devices to include an MPTCP kernel.

Over-the-top (OTT), software-only aggregation solutions, however, can be implemented irrespective of what cellular network assets the MSOs own. OTT aggregation solutions are easy to implement and do not require MSOs to own licensed spectrum or have access to LTE network components, so they are attractive solutions for traditional MSOs and light and full MVNOs. OTT aggregation solutions can also be implemented by MSOs who own a complete cellular network, allowing them to make the best use of all their assets. For MSOs that do not own a cellular network, OTT aggregation will allow them to leverage enhancements made on cellular networks by MNOs, coupling them with Wi-Fi network enhancements on MSO networks to provide an aggregated data rate that enhances network performance for the end user.

The key advantages of OTT aggregation solutions over other aggregation technologies include the following:

- high data rates that are economically achievable because no changes to existing LTE and Wi-Fi networks are required and with no additional device support is needed,
- gapless handovers with IP continuity and bandwidth aggregation across all heterogeneous networks,
- ability to set customized policies and manage QoS (Quality of Service) without access to MNOs' EPC, and
- ability to aggregate an MSO-owned Wi-Fi network with third-party (private) CBRS networks.

The advantages of OTT aggregation make it an economical way for MSOs to provide higher data rates and thereby enhance user experience, especially when compared with traditional and standardized aggregation solutions.