Seamless Connectivity

Transitioning Between Wi-Fi And Other Radio Access Networks

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1. Introduction to Seamless Connectivity

Seamless connectivity refers to the ability of a device to maintain a stable and uninterrupted internet connection as it transitions between different types of networks, such as Wi-Fi® and cellular networks. In the context of seamless transition while moving between Wi-Fi and cellular, it ensures that the user experiences service continuity without noticeable interruptions or degradation in performance, regardless of changes in network environment.

MNOs (mobile network operators) want to leverage Wi-Fi network deployments to offload the traffic from cellular networks. With the advent of 5G and the use of mmWave frequencies, indoor coverage has become more challenging due to the limited penetration and short range of mmWave signals. Although these issues can be addressed with dense small cell deployments, advanced beamforming, and hybrid network integration, leveraging the widespread Wi-Fi deployments in indoor environments significantly reduces costs. MSOs (multiple systems operator) or MVNOs (mobile virtual network operator) who resell cellular network from MNOs (mobile network operator) want their subscribers to leverage their carrier grade Wi-Fi, community Wi-Fi and home broadband Wi-Fi offerings whenever the Wi-Fi network quality is good enough to meet the service requirements.

Given most of the devices today use a "Wi-Fi First" approach prioritizing Wi-Fi connections over cellular for data transmission when the device can access an available Wi-Fi network, Wi-Fi offload for seamless transition of devices from cellular to Wi-Fi can be achieved. However, because of the "Wi-Fi First" approach, transition from Wi-Fi to cellular causes challenges, where devices stay connected to the Wi-Fi network even when the Wi-Fi network quality is too poor to address the users' service requirements and a better performing cellular network is available (commonly known as a "sticky-client" issue). Assuming the device can connect to both available Wi-Fi and cellular networks simultaneously, the key challenge is ensuring that the transition between those networks is fast with minimal to no impact on user experience.

The ways in which a device can prioritize between multiple available Wi-Fi networks (carrier grade Wi-Fi, community Wi-Fi, in home Wi-Fi, etc.) have been investigated within Wi-Fi standard bodies. However, the triggers and thresholds used for initiating a device transition between Wi-Fi and cellular vary across different chipsets, operating systems, OEMs (original equipment manufacturer), and carrier locked devices does not have any defined standards.

Certain over-the-top (OTT) solutions and new 5G features such as Access Traffic Steering Switching and Splitting (ATSSS) enables operator to leverage both access technologies (Wi-Fi and cellular) simultaneously and define policies to steer, switch and/or split traffic dynamically. However, VPN-like (virtual private network) OTT solutions may incur security concerns, overheads, and other potential issues, while ATSSS feature implementation requires operators to own a 5G core. Traditional, siloed network architectures where the Wi-Fi and cellular networks operate independently and only one can be used at any given point in time, require an IP address change for the device at the application layer making seamless connectivity without service disruption challenging. It should be noted that mobile applications have become more resilient to connectivity disruptions, so the IP address change is becoming less of an issue but will continue to cause some user experience degradation.

Given the significance of this issue, CableLabs® in collaboration with its members conducted in-house testing for seamless connectivity when transitioning between the Wi-Fi and cellular networks. CableLabs recognizes the evolving mobile industry landscape driven by the introduction of 5G and the availability of new and innovative spectrum options. With a growing mobile subscriber base of our members that complements their existing broadband and cable offerings, we understand the need to resolve the pain points that our members face today (or may face in the near future). This technical paper summarizes the testing that attempted to:

- Validate whether the “sticky client” issues exist. If yes, quantify how often this problem exists and under what conditions.
- Characterize the behavior of a representative sample of devices (in terms of chipsets, operating systems, OEMs, etc.) and the impact on end user experience.
- Identify the metrics and thresholds being used to trigger the transition.
- Measure the time taken to transition and how seamless the user experience is.

2. Seamless Connectivity: Transition Scenarios

Seamless connectivity is an overloaded term in the wireless industry. In the broadest sense, it means ubiquitous, continuous/seamless/unbreakable connectivity for all devices, at any time, regardless of the location, without any performance degradation. Generally, the underlying technical aspects of seamless connectivity include network availability, network discovery, network selection, network authentication, network registration/attach/connectivity and network transition. This paper investigates seamless connectivity for end-user devices, focusing on their ability to efficiently transition and connect to available Wi-Fi or cellular networks at any given moment. It is assumed that both Wi-Fi and cellular networks are available, and the device possesses the necessary credentials for connection.

The emphasis in this paper is on efficiently transitioning between Wi-Fi and cellular networks considering the network quality and the requested service (and its associated requirements) to always connect to the best available network. This efficient transition can help avoid user frustration and may keep users from manually disabling the Wi-Fi. The type of Wi-Fi network (carrier grade Wi-Fi, community Wi-Fi, in home Wi-Fi, etc.) or cellular network (4G/5G) should not matter with regards to transition triggers and thresholds, in most of the cases, unless there are operator specified preferences for these networks.

This transition can be triggered by two factors: the User Equipment (UE), a smartphone in this case, moving out of the network coverage area (mobility-based) or the network becoming congested, forcing the UE to disconnect (congestion-based).

2.1. Mobility-based transition

Mobility-based transition occurs when the UE transitions between Wi-Fi and cellular networks based on the UE moving in/out of the network coverage area. The device, when inside the coverage of both Wi-Fi and cellular networks, uses the Wi-Fi network for data transmission (Wi-Fi First). As the device moves outside the Wi-Fi coverage area it transitions from Wi-Fi to cellular. Conversely, re-entering Wi-Fi coverage triggers a switch back to Wi-Fi.

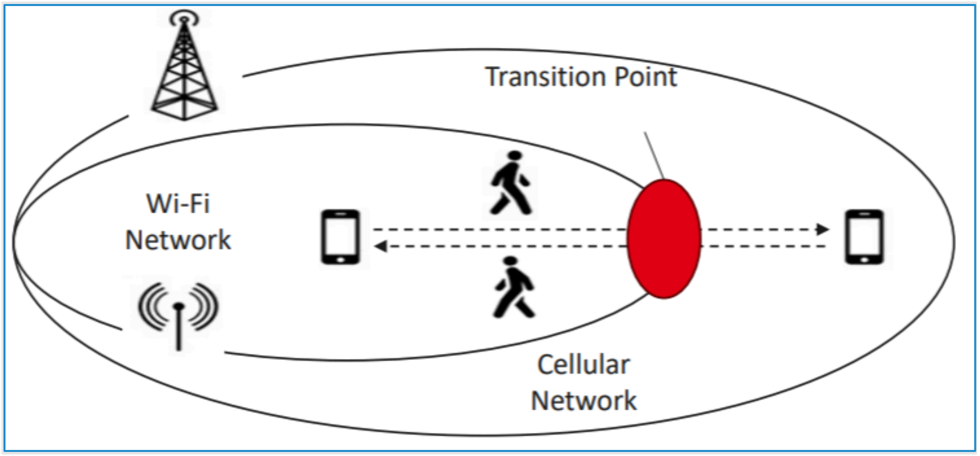

Figure 1 – Mobility-based Transition

2.1.1. Cellular to Wi-Fi

For a cellular-to-Wi-Fi transition, it is assumed that the device is initially outside of any Wi-Fi coverage area and has an active data session on the cellular network. The figure below depicts the various steps involved in this scenario.

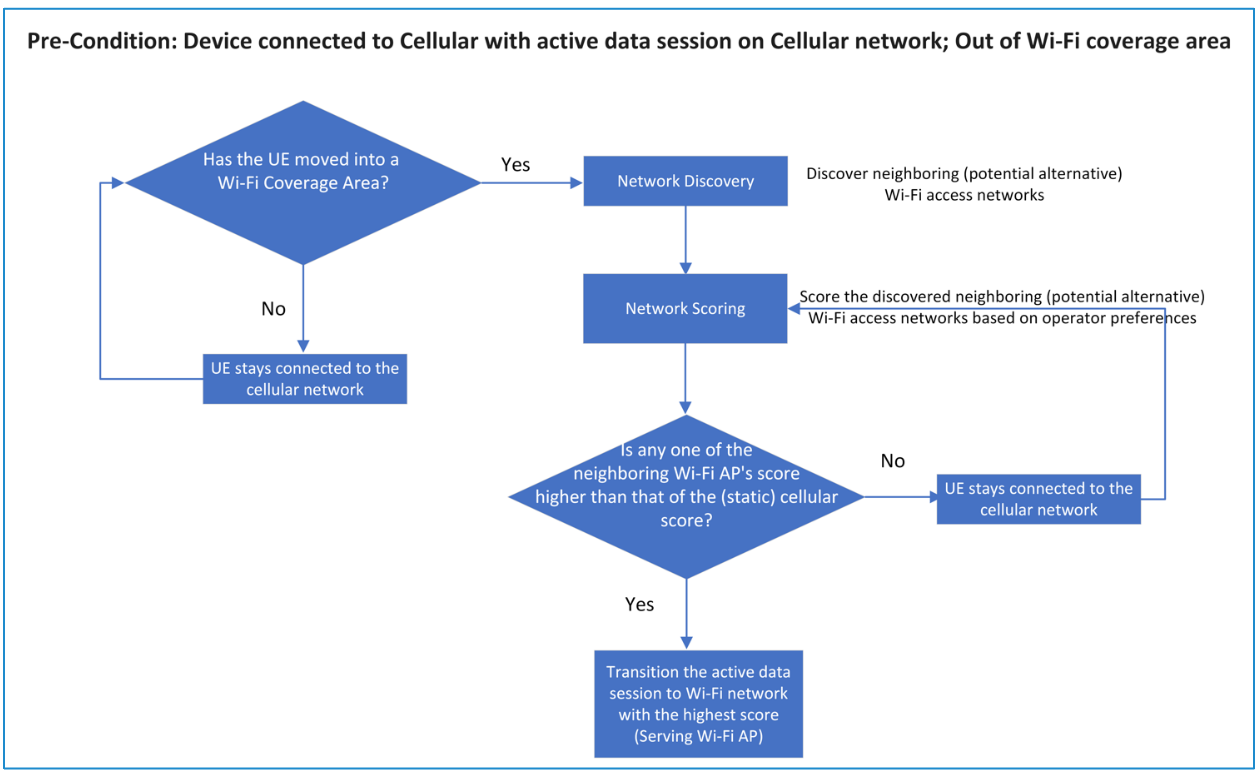

Figure 2 – High-level cellular to Wi-Fi Transition Flow

2.1.2. *Wi-Fi to Cellular*

For a Wi-Fi to cellular transition, the device is assumed to be within both Wi-Fi and cellular coverage (since it is assumed that cellular coverage is widespread) and has an active Wi-Fi data session. The transition to cellular occurs when the device moves outside Wi-Fi coverage.

The transition flow is similar to the transition from cellular to Wi-Fi, with one key difference: if the device can discover a better performing Wi-Fi network during the transition, it may attempt to connect there before switching to cellular (Wi-Fi First).

If no alternate Wi-Fi network is detected, and the quality of the connected Wi-Fi network deteriorates significantly, the device, theoretically, seamlessly transitions the ongoing data sessions from Wi-Fi to cellular. The end device chooses a particular network (Wi-Fi or cellular) based on a network "score" which is calculated by vendor-specific algorithms running on the end device.

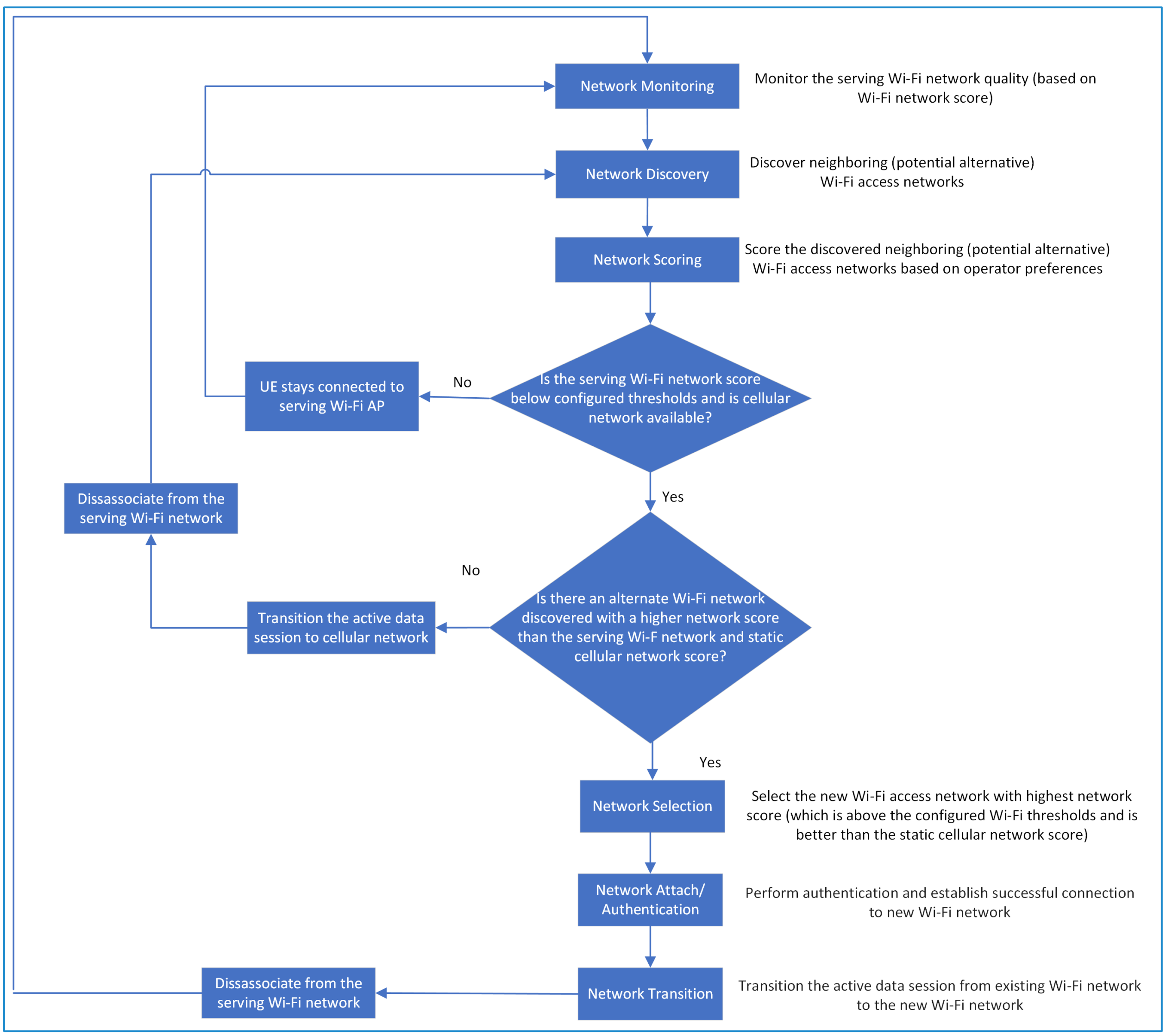

Figure 3 – Wi-Fi to Cellular Transition Flow

Note: Because most UEs prioritize Wi-Fi connections (Wi-Fi First implementation), they may continue searching for Wi-Fi networks even when in vicinity of good cellular coverage. Based on the underlying algorithms from either the chipset manufacturer, Operating System (OS) provider/Original Equipment Manufacturer (OEM)/Application provider, the device would prefer to connect to and stick to the Wi-Fi network. This behavior can lead to increased airtime usage in poor Wi-Fi coverage areas and may potentially degrade the performance of the ongoing traffic session.

Additional details on the device's behavior are described in the Testing Overview section below.

2.2. Congestion-based Transition

Congestion-based transition occurs when the device transitions between Wi-Fi and cellular networks based on network congestion (e.g., surge in users, channel interference, bandwidth intensive applications, reduced available airtime etc.). In this situation, the device is inside the coverage of both Wi-Fi and cellular network and uses the Wi-Fi network for data transmission (Wi-Fi First). Theoretically, as the Wi-Fi network gets congested, the device transitions from Wi-Fi to cellular and, as the congestion is reduced, it transitions back from cellular to Wi-Fi.

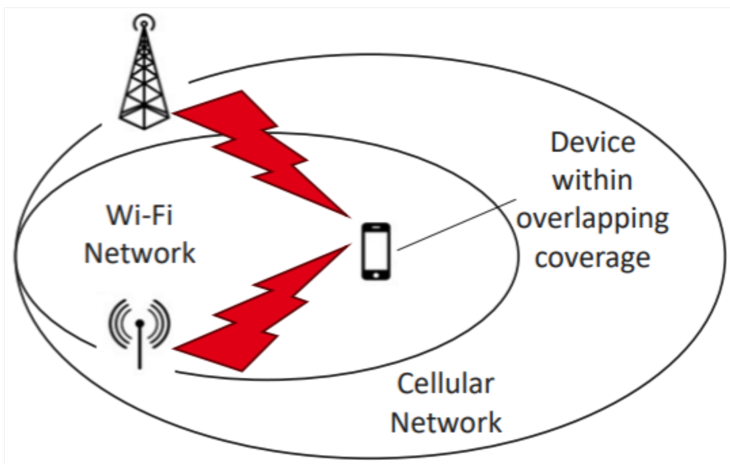

Figure 4 – Congestion-based Transition

2.2.1. *Wi-Fi to Cellular*

When Wi-Fi network congestion occurs, the UE experiences degraded network performance, such as reduced throughput, higher latency, and increased packet error rates. This triggers the UE's transition algorithm, as detailed in the previous section. This algorithm involves network discovery, scoring, selection, authentication/connection, and the actual transition process. Furthermore, if the UE moves out of Wi-Fi coverage and if the cellular network scores higher, the UE will transition to cellular data, which is the mobility-based transition.

2.2.2. *Cellular to Wi-Fi*

Similar to Wi-Fi to cellular transition, cellular network congestion can trigger the UE's transition algorithm. In this case, the UE would evaluate available Wi-Fi networks and choose the one with the best network score.

Note that our current testing focussed on mobility-based transitions only, however, we view the congestion-based transitions equally important to ensure the best quality of experience (QoE) for the stationary users. Our further testing efforts will attempt to quantify and validate this scenario.

3. Ecosystem: Components Influencing Seamless Connectivity

There are many components in a UE that will influence when, or how well, it transitions between Wi-Fi and cellular. This section talks about each component starting with the lowest-level component, the chipset being used to the highest-level component, the application running on the UE.

3.1. System on Chip (SoC)/Chipset Manufacturers

The chipset within a UE is fundamental in determining the device's overall capabilities and behavior, especially regarding connectivity, processing power, and efficiency.

- **Hardware Capabilities, Firmware and Drivers:** Chipset manufacturers design hardware through integrated modem solutions that support multiple radio technologies (Wi-Fi, cellular, Bluetooth, etc.) defining capabilities and efficiencies of these radios crucial for seamless switching. They provide firmware and drivers that manage the low-level operation of network interfaces for maintaining stable connections and enabling fast switching.
- **Power Management:** Chipsets may include certain power management features (such as dynamic power scaling and advanced battery charging) that can help determine when to switch networks to optimize battery life and manage power consumption by turning off unused interfaces when not needed.
- **Interfacing with the Operating System:** Chipset may provide APIs (application programming interface) for the OS to access network status, manage connections, and execute transitions. This allows higher-level software to coordinate with the operating system to implement user policies and preferences and manage user notifications, permissions, and other interface elements related to network transitions.

3.2. Operating System

The OS plays a crucial role in managing network transitions in an attempt to ensure seamless connectivity between Wi-Fi and cellular networks. This involves a complex interplay of system services, APIs, and algorithms designed to evaluate network conditions, manage connections, and handle transitions efficiently and securely.

Between the mobile operating systems, the differences with regards to Wi-Fi and cellular network transition may stem from their distinct approaches to system architecture, user control, customization options, and integration with hardware.

3.2.1. Network Monitoring and Management

The OS manages multiple network interfaces, such as Wi-Fi and cellular, and ensures they are configured and operational. This involves handling the enabling and disabling of interfaces, initiating network scans, and managing connections. It continuously monitors the status of all network interfaces to determine connectivity conditions. It uses system services and background processes to keep track of signal strength, connection quality, and availability of networks.

3.2.2. Network Evaluation and Selection

The OS evaluates available networks based on various metrics like signal strength, link speed, and reliability. It assigns scores to networks and prioritizes them to select the best available network for connection. It implements decision-making algorithms that determine when to switch networks based on predefined criteria, such as signal degradation, loss of connectivity, or user preferences.

3.2.3. Connection Management

The OS attempts to manage the handover process between Wi-Fi and cellular networks to ensure minimal service disruption. It attempts to preserve the state of active sessions during transitions to avoid disruptions and ensures ongoing activities, such as voice calls or video streaming, continue seamlessly without noticeable interruptions.

3.2.4. Application-Level Support

The OS provides high-level APIs for applications to access network status and control network operations that enable applications to:

- Request specific network capabilities and receive notifications about network changes
- Manage QoS parameters to try to prioritize critical data traffic during transitions
- Try to ensure that they receive the necessary bandwidth and low latency to maintain performance

3.2.5. User Preferences and Policies

The OS offers user-configurable settings to control network behavior, such as preferring Wi-Fi over cellular for data usage or enabling/disabling automatic network switching. It provides interfaces in system settings for users to specify their preferences. It can enforce user-defined policies and system-level policies to manage network transitions and ensure compliance with user preferences while optimizing for performance and connectivity.

3.2.6. Battery/Power Management

The OS optimizes power consumption by managing the activation and deactivation of network interfaces based on usage and conditions. It uses efficient algorithms for network scanning and evaluation to balance connectivity performance with battery life. It adapts power strategies based on user activity and network conditions, such as reducing scan frequency when the device is idle and implements power-saving modes that selectively disable or reduce the activity of network interfaces when not in use.

3.3. Original Equipment Manufacturers

Original Equipement Manufacturers (OEM) often implement customizations and enhancements to improve network transitions between Wi-Fi and cellular networks. These customizations aim to enhance user experience, optimize connectivity, and differentiate their devices in the market. OEMs may include additional software or utilities that influence network transition behavior (e.g., battery-saving modes, performance optimizers). To ensure seamless network transitions, OEMs can develop proprietary algorithms that enhance the default network selection and switching behavior provided by Android. These algorithms can be optimized based on device hardware capabilities and customized for intended operator use cases.

3.3.1. Enhanced Network Evaluation and Decision Algorithms

OEMs may implement features that use enhanced algorithms to evaluate the stability and speed of Wi-Fi connections and to make transition decision towards cellular if Wi-Fi quality drops below a certain threshold. These enhancements involve real-time assessment of network conditions, historical data analysis, and user behavior prediction to ensure seamless connectivity and an improved user experience.

Some OEMs offer features which enable intelligent switching between Wi-Fi and cellular networks based on network quality. Some implement advanced AI-based algorithms that learn user behavior and network conditions to predict and evaluate network performance, ensuring a smoother transition between Wi-Fi and cellular networks.

3.3.2. Advanced Connectivity Management Features

OEMs may enhance network transitions and overall connectivity experience by implementing advanced connectivity management features. These features are designed to optimize network performance, improve user experience, and ensure seamless transitions between Wi-Fi and cellular networks.

Some OEMs use features which automatically switches to cellular data when a Wi-Fi connection is weak or unstable. This ensures that users maintain a seamless internet experience without manual intervention. Some OEMs manage transitions between Wi-Fi and cellular networks by prioritizing the best available connection based on real-time network performance and usage patterns.

3.3.3. Dual Connectivity and Simultaneous Network Usage

OEMs may implement features that aid in seamless transitions by maintaining connectivity to one network while switching to another ensuring users get the best of both networks, reducing the time needed to transition between them.

Some OEMs include features that allow the device to connect to two Wi-Fi networks simultaneously, providing faster and more stable internet connectivity, while some OEMs implement features that combine Wi-Fi and cellular connections to accelerate download speeds for large files.

3.3.4. Power Management Enhancements

OEMs may implement features that ensure that network transitions do not excessively drain battery power by restricting background network usage, intelligently optimize network scan intervals and connections based on usage patterns. These features may negatively impact seamless transitions between Wi-Fi and cellular networks.

Some OEMs optimize battery usage by managing network activities while some OEMs present custom power management settings that help optimize network transitions thereby saving battery life.

3.3.5. Security and Privacy Enhancements

OEMs may implement features that ensure network transitions do not compromise user privacy and data remains protected even when transitioning between networks.

To enhance privacy, some OEMs make use of private MAC (media access control) addresses for Wi-Fi networks, preventing tracking across different Wi-Fi networks, while some OEMs encrypts internet traffic over unsecured Wi-Fi networks, providing additional security during network transitions.

3.3.6. User Interface and Experience Enhancements

OEMs may implement features that help users understand when and why transitions occur and allow users to manage network preferences and get detailed information about network performance, aiding in smoother transitions.

Some OEMs include enhanced notifications and user interface elements that inform users about network quality and transitions while some OEMs provide users with insights and control over their network connections.

3.4. Network Operators

Network operators may significantly influence the transition between Wi-Fi and cellular networks through policies, infrastructure, and services designed to enhance seamless connectivity. By implementing advanced network optimization techniques, customizing device configurations, and leveraging real-time data, operators can attempt to ensure smooth transitions and improved user experiences. This is often a collaborative approach between operators and OEMs and is crucial for delivering reliable and efficient connectivity in a constantly evolving digital landscape.

3.5. Application on the UE

Applications running on the UE may have some influence on their data streams network path.

3.5.1. Seamless Transition Management

Applications may use MPTCP (multi-path TCP)/MPQUIC (multi-path QUIC) to maintain multiple active connections over both Wi-Fi and cellular simultaneously, allowing for seamless transitions without dropping calls or losing data and maintaining persistent socket connections (e.g., WebSocket's), in the presence of network changes, without requiring re-establishment.

3.5.2. Adaptive bitrate streaming

Applications may adjust the quality of video and audio streams using scalable codecs based on the available network conditions ensuring seamless network transition between Wi-Fi and cellular. During a transition, it may temporarily lower the quality to avoid interruptions and then scale back up once the new connection stabilizes.

3.5.3. Data Usage Optimization

Applications may allow users to control when and how cellular data is used, such as restricting high-bandwidth activities to Wi-Fi only and performing intelligent caching on Wi-Fi to minimize cellular data usage once the transition occurs.

3.5.4. Real-time Monitoring

Applications may monitor the quality of the network connection. If the Wi-Fi signal weakens or is lost, automatically switch to cellular data to maintain the connectivity at all times and use contextual information (e.g., whether the device is stationary or moving) to make informed decisions about when to switch networks.

3.5.5. Error Resilience

Applications may employ error resilience techniques to minimize the impact of packet loss and latency during network transitions, ensuring that the user experience remains consistent

3.5.6. Notification and Control

Applications may provide users with notifications if the network quality degrades, allowing them to switch networks manually if needed.

3.5.7. Application Control of Network

Application developers may have the ability to control which network, Wi-Fi or cellular, is used for the application's data stream, if multiple paths are available.

4. Testing Overview

The in-house testing at CableLabs focused on the Mobility scenario while transitioning between the Wi-Fi and cellular networks. The goal of the testing was two-fold:

1. Characterize the device behavior during transitioning – specifically at what level of RSSI is the Wi-Fi network deemed to not be good enough thereby transitioning to a cellular network (assuming another better performing Wi-Fi network is not available).

2. Validate the impact on the user experience during the transition phase – not just focusing on the transition time, but also the time before the transition where the network quality is poor. For example, the inefficient transition of the UE from Wi-Fi to cellular by trying to stick to the Wi-Fi networks resulting in service degradation.

4.1. Test Setup

The test setup comprised of a commercial cellular network and a test Wi-Fi network along with commercial off the shelf (COTS) UEs acting as a device under test (DUT). The DUTs were equipped with a SIM (subscriber identity module) that had necessary credentials for connecting to the commercial cellular network. The DUTs were also configured with the necessary credentials to connect to the test Wi-Fi network while ensuring it does not have credentials to connect to any other known Wi-Fi networks. This ensured that when the DUTs moves away from the test Wi-Fi network, DUTs will have to transition to the cellular network with no other better performing Wi-Fi network available. The cellular network coverage was assumed to be ubiquitous and stable. The Wi-Fi network was broadcasting a single SSID (service set identifier) and was configured as shown in Table 1:

Table 1 – Wi-Fi Access Point Configuration

Configuration Setting	Value
Channel	157
Standard	Wi-Fi 5
Channel Bandwidth	80 MHz
Security	WPA2-Personal
Encryption	AES
Beacon Interval	102.4ms

4.2. Test Tools

The test results were captured using multiple test tools. On some of the DUTs, using the developer options, device internal logs were captured containing the network events and vendor specific events in the system logs (e.g., connection and disconnection from Wi-Fi, Wi-Fi RSSI, etc.). When running applications during the mobility scenarios, real-time network and application KPIs (e.g., round trip time (RTT), throughput, etc.) were captured using either app-based tools or over-the-top (OTT) applications.

4.3. Test Methodology

For testing the transitions between the Wi-Fi and cellular networks, the DUT was physically moved to simulate real-world mobility scenarios. The DUT was placed on a movable cart, so that the positioning of the DUT and body loss would not skew the test results. The testing was performed both with active user traffic (e.g., real-time RTP (real-time protocol) traffic, live video streaming, etc.) and without active user traffic. All the test results are average values of multiple tests.

For Wi-Fi to Cellular transitions, the device was placed within the coverage of both Wi-Fi and cellular network and then moved away from the Wi-Fi access point coverage to trigger a transition to cellular network.

For Cellular to Wi-Fi transition, the device was placed within the coverage of the cellular network only and then moved towards the Wi-Fi access point to trigger a transition to the Wi-Fi network after the Wi-Fi network RSSI improved significantly as the DUT moved inside the Wi-Fi coverage.

The scenario where the device may be at a location where there is no cellular coverage (cellular coverage hole) was not considered during this testing effort.

4.4. Test Results and Key Observations

The results captured below are either with optimized or non-optimized user settings on the DUT. Optimized user settings means the mobile/cellular data is always enabled, the setting to use mobile data when Wi-Fi connection is slow or unstable is enabled, and the setting to extend battery life and improve performance by automatically managing network connections is enabled. Unoptimized user settings means that all of these settings are disabled. Each DUT may have one or more of these user settings available and these setting names may differ across different OEMs.

Table 2 captures the RSSI levels during network transitions in both directions with and without live-stream HD traffic including the user experience during Wi-Fi to cellular transition. Note that the data captured in both Table 2 and Table 3 is for the optimized user settings on the DUT. Table 2 also notes the duration of the user's poor experience, defined as starting when the first 2-second hang or dropout occurs and if subsequent hangs or drops occur within the next 5 seconds, ending when the drops or hangs no longer occur and the data stream is on cellular. Note that RSSI is the signal level the DUTs measured the received the AP's transmissions at.

Table 2 – Using Optimized Settings, transition RSSI levels both with and without Live-stream HD traffic

DUT	Traffic	RSSI at transition [Wi-Fi to Cellular] (in dBm)	RSSI when Wi-Fi gets disconnected	RSSI at transition [Cellular to Wi-Fi] (in dBm)	[Wi-Fi to Cellular] Poor User Experience Duration
DUT1	Without Traffic	-85	-86	-76	N/A
	With Traffic (Live Video Streaming)	-85	-87	-77	No video gaps observed
DUT2	Without Traffic	-77	-85	-73	N/A
	With Traffic (Live Video Streaming)	-77	-86	-73	Multiple 2 to 5 second video gaps in 2 of 7 test runs
DUT3	Without Traffic	-91	-91	-77	N/A
	With Traffic (Live Video Streaming)	-85	-92	-69	Multiple 5 to 17 second video gaps in 3 of 10 test runs
DUT4	Without Traffic	-85	-86	-73	N/A
	With Traffic (Live Video Streaming)	-86	-87	-74	No video gaps observed, except for one outlying test run

Table 3 – Video calling traffic vs. video streaming traffic, transition time

DUT 2	Wi-Fi => Cellular		Cellular => Wi-Fi	
	Poor User Experience Duration	Data Transition Duration	Poor User Experience Duration	Data Transition Duration
Video Conference	78s	10s	0.1s	0.1s
Streaming	14s	3s	0s	0s

The reason Table 2 shows poor user experience duration only for Wi-Fi to cellular transition is highlighted in Table 3. Table 3 shows the impact on the poor user experience duration and data transition duration when moving in either direction for a single DUT as an example (similar data was observed for other DUTs as well). Data Transition Duration is defined as the time from the last packet sent by the application on one radio interface to the first packet sent by the application on the other radio interface.

Key Observations from Table 2 and Table 3:

1. The RSSI thresholds to trigger the transition between Wi-Fi and cellular (in both directions) are not consistent across different DUTs (with different chipsets, OSs and OEMs).

2. Some DUTs use the same RSSI thresholds to trigger the transition between Wi-Fi and cellular (in both directions) when there is ongoing active data session while some DUTs use different RSSI thresholds when there is or is not ongoing user traffic.

3. The impact on user experience when there is ongoing user traffic during the network transition varies significantly across DUTs.

4. The poor user experience duration, and the data transition duration are higher when transitioning from Wi-Fi to cellular than in the other direction

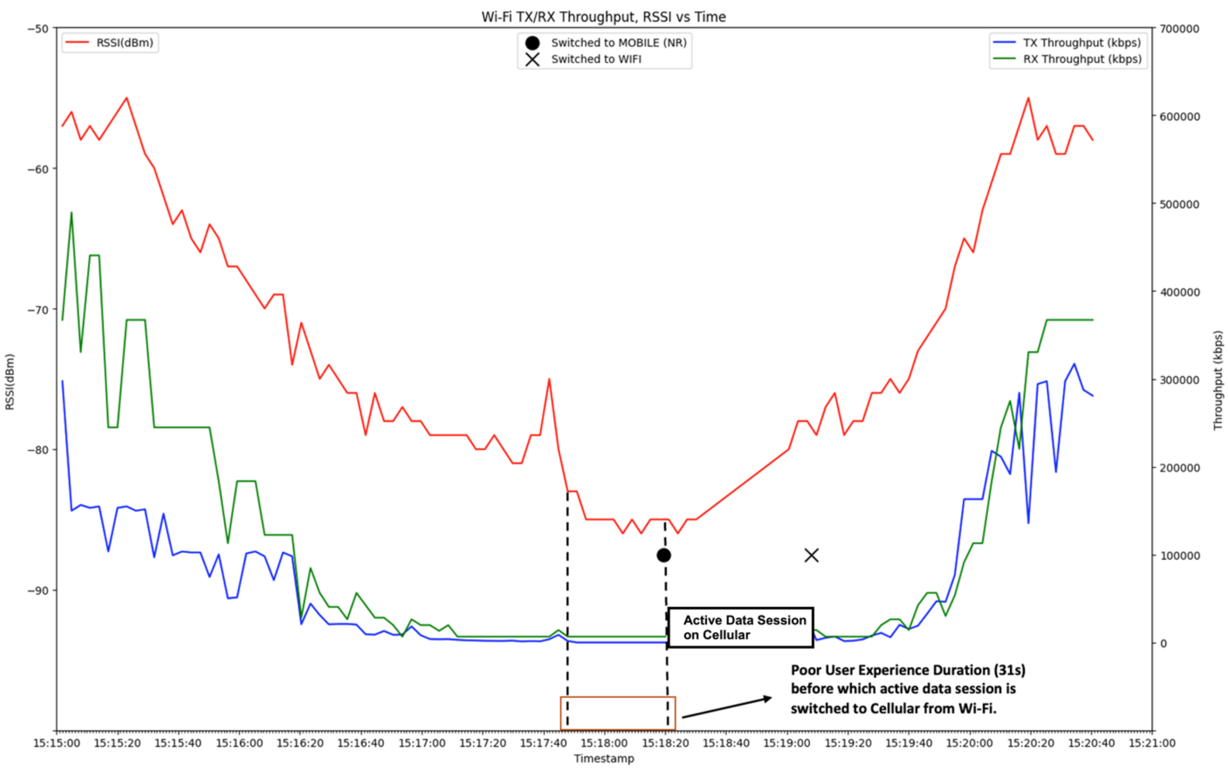

Figure 5 – *DUT 2 Unoptimized Settings: Wi-Fi Throughput and RSSI vs. Time*

Figure 5 shows the network transition where a DUT with an active data session is initially connected to both cellular and Wi-Fi with an active data session on Wi-Fi, and is then moved outside the Wi-Fi coverage. This triggers a transition to the cellular network (depicted by the black dot), and then the UE is moved back inside the Wi-Fi coverage triggering a transition back to the Wi-Fi network (depicted by the black 'X'). The two dashed lines represents the period (31 seconds) where the live video stream experience issues (choppy audio and video intermittently pausing) which highlights the period where the user experienced poor Wi-Fi network quality but where the UE has not yet transitioned to a better performing and available cellular network. Note that this is not the time taken to transition from Wi-Fi to cellular (last user data packet on Wi-Fi and first user data packet on cellular). The time between the black dot and the black cross represents the time when the DUT is on the cellular network. Note that the figure does not show any cellular KPIs for the time DUT is on the cellular network. Another the key thing to note is the data in Figure 5 shows the results for unoptimized user settings on the DUT.

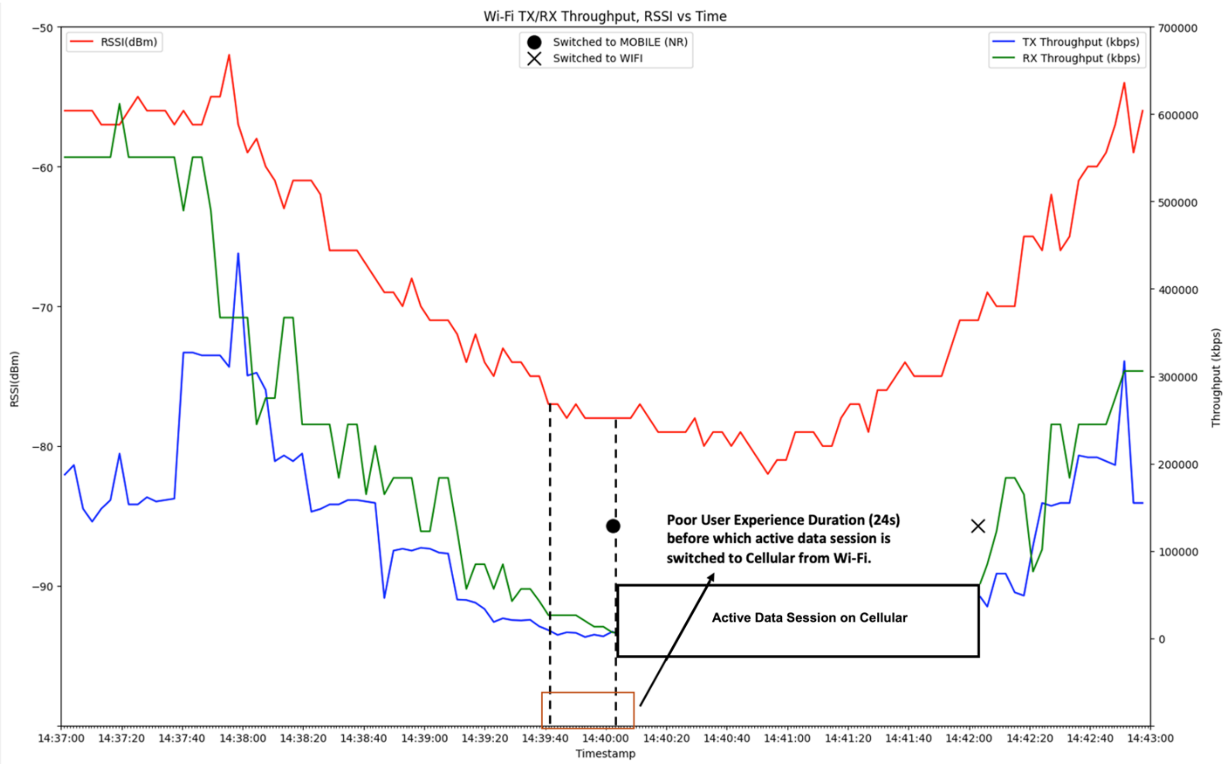

Figure 6 – *DUT 2 Optimized Settings: Wi-Fi Throughput and RSSI vs. Time*

Similar to Figure 5, Figure 6 shows the network transition where the DUT with an active data session is initially connected to both cellular and Wi-Fi with an active data session on Wi-Fi, and is then moved outside the Wi-Fi coverage. Again, this triggers a transition to the cellular network (depicted by the black dot), and then the UE is moved back inside the Wi-Fi coverage triggering a transition back to the Wi-Fi network (depicted by the black cross). The key difference in Figure 2 is that the DUT had optimized user settings. With optimized settings, we see the transition threshold is at a higher RSSI (more aggressive threshold), thus reducing the poor user experience duration between the two dashed lines (to 24 seconds) where the live video stream started to experience some issues.

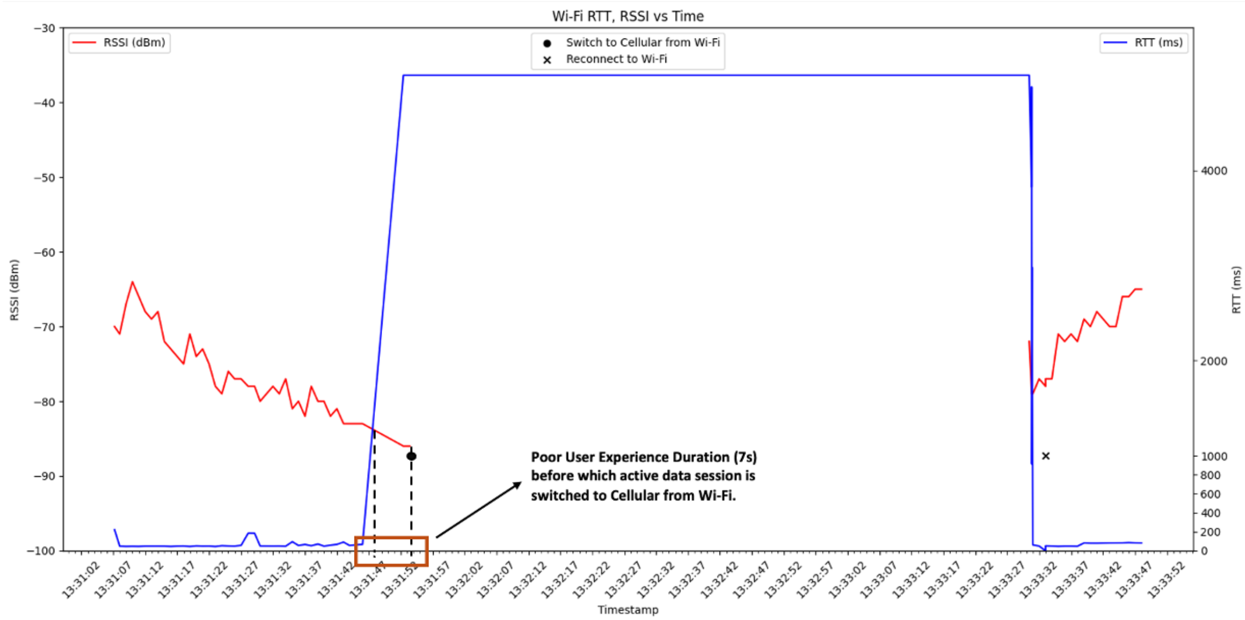

Figure 7 – *DUT 4 with Unoptimized Settings: Wi-Fi RTT and RSSI vs. Time*

Figure 7 shows RSSI (of the AP's transmissions) and Round-Trip Time (RTT) of an HTTP Request/Response, over Wi-Fi only, for DUT 4 in the same mobility test scenario as Figure 5 and Figure 6. In this test, the unoptimized settings are used. In addition to the HTTP Request/Response traffic, the DUT was also showing a real-time video feed. As seen from the red box, the user experienced 7 seconds of poor user experience video playback as the UE moved out of Wi-Fi coverage before the UE switched the data streams to cellular. At the same time the HTTP RTT times out (5000 ms maximum) until the UE comes back into Wi-Fi coverage and reconnects to Wi-Fi.

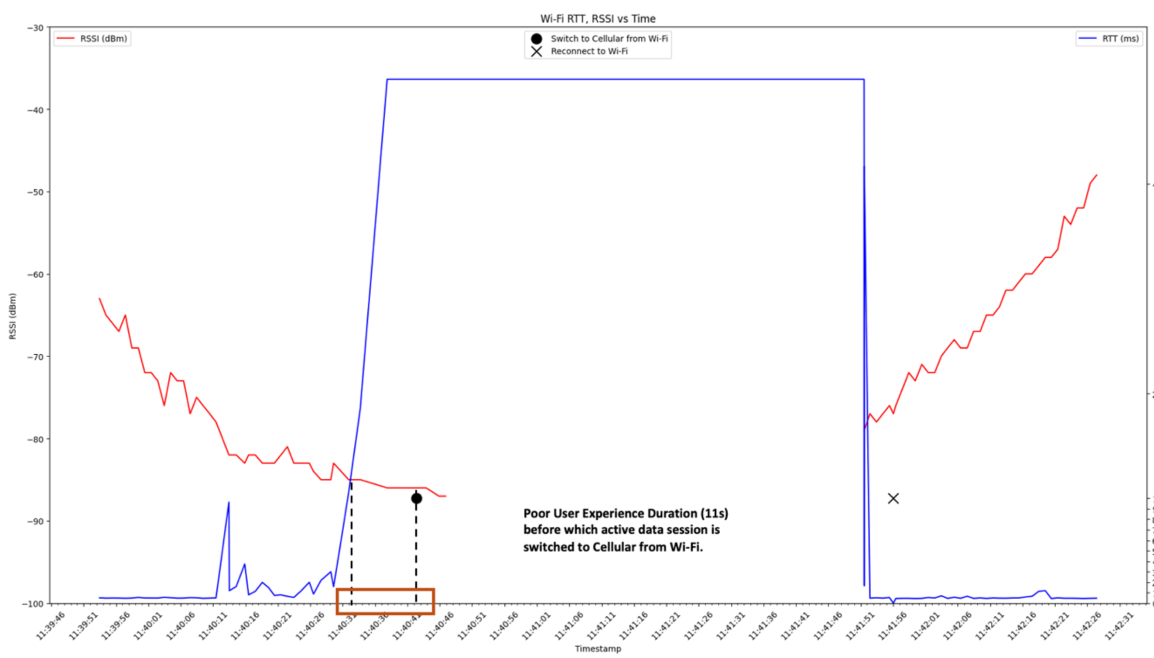

Figure 8 – *DUT 4 with Optimized Settings: Wi-Fi RTT and RSSI vs. Time*

Interestingly, Figure 8 shows the same test as Figure 7 but with optimized settings turned on, yet the poor user experience time is longer. Furthermore, the RSSI level at which the phone switched data streams to cellular is the same. It therefore does not appear that the optimized settings for DUT 4 improved anything in the scenario we tested.

Key Observations from Figure 5 through Figure 8:

1. The time that the user has a poor experience, again, varies significantly across DUTs.

2. The results of optimization settings vary widely across DUTs. They impact the RSSI thresholds to trigger the transition between Wi-Fi and cellular on some DUTs and not others (with different chipsets, OSs and OEMs). Sometimes the settings improve the user experience but sometime they make it worse.

Overall Conclusions:

1. The device behavior with regards to network transition is inconsistent and the user experience significantly varies based on the device (chipset, OS, OEM and sometimes even network operator in case of carrier blocked phones).

2. The impact on user experience with regards to service disruption and time taken to transition the data across networks is much higher when moving from Wi-Fi to cellular than in the other direction.

3. Some of the stakeholders have worked to improve this Wi-Fi to cellular transition and, while some have made improvements, there is still room for a much better user experience.

5. Existing Solutions Survey

The current solutions for seamless transitioning, defined and/or deployed, span a very wide area. Multiple standards were developed to address the problem from the cellular or Wi-Fi side. Separately, there are many Over-The-Top solutions that do not rely on standards, and that may or may not require external elements in the network (e.g., aggregation or VPN servers). At the root of solutions that attempt to address the problem are the KPIs that can be used to understand when to have devices transition from one radio access network (RAN) to another. This section gives an overview of the possible solutions as of the time of this writing.

5.1. Standards Development Organizations (SDOs) Initiatives

5.1.1. 3GPP™ ATSSS (Access Traffic Steering, Switching, and Splitting)

The 3rd Generation Partnership Project (3GPP) is a collaboration between groups of telecommunications standards bodies, known as the Organizational Partners. The key functions include standards development, global collaboration and technological evolution. The goal of 3GPP is to create globally applicable technical specifications covering various generations of mobile technology, including 3G (UMTS), 4G (LTE), and 5G NR (New Radio). These specifications and standards are crucial for ensuring that devices and networks from different manufacturers can work together seamlessly, providing reliable and efficient mobile communication services worldwide.[3]

Understanding the proliferation of diverse access technologies (e.g., 4G, 5G, Wi-Fi) and the increasing heterogenous nature of operator deployments, 3GPP introduced ATSSS feature in 3GPP Rel-16 for seamless and efficient utilization of these networks to enhance user experience and optimize resource usage by enabling devices to intelligently manage traffic across multiple access networks. ATSSS provides mechanisms for traffic steering, switching, and splitting between different access networks (such as 5G and Wi-Fi).

- **Traffic Steering**: Directing traffic flows to the most appropriate access network based on predefined policies, network conditions, and application requirements.
- **Traffic Switching**: Seamlessly transferring ongoing traffic from one access network to another without disrupting the session, ensuring continuous connectivity.
- **Traffic Splitting**: Distributing traffic flows across multiple access networks simultaneously to optimize performance and reliability.

Benefits

- **Improved User Experience**: By dynamically managing traffic, ATSSS ensures that users experience minimal disruptions and optimal performance, even when moving between networks.
- **Enhanced Resource Utilization**: Efficient use of available network resources by dynamically distributing traffic based on network conditions and capacity.
- **Increased Reliability and Redundancy**: Traffic splitting across multiple networks provides redundancy, reducing the likelihood of service interruptions.
- **Policy-Based Control**: Operators can define policies to prioritize certain traffic types, optimize network load, and enhance service delivery based on business objectives.

5.2. Wireless Broadband Alliance (WBA)

The Wireless Broadband Alliance (WBA) is a global standards organization that enables collaboration between service providers, technology companies and other standards organizations to drive seamless and interoperable services experience via Wi-Fi.

5.2.1. Access Network Metrics

WBA's Access Network Metrics Working Group (WG) aims to develop a framework which would enable Wi-Fi equipment vendors to define and expose Wi-Fi Quality of Experience (QoE) centric metrics to the stakeholders including the operators and Wi-Fi end user consumers. Furthermore, this framework would also be useful for analyzing and aggregating the Wi-Fi metrics which would produce additional processed metrics to the customers which would aid in a better understanding of Wi-Fi network selection. The following are the network metrics/ KPIs that the WG has defined in its Phase 1 work:

- Device RSSI
- AP Noise Floor
- AP Tx MCS (modulation and coding scheme index)
- Device Tx MCS
- Wi-Fi Latency/ Jitter
- Airtime Utilization
- Frame Retries
- Frame Loss Rate
- Radio Type

Future work includes aggregating and analyzing a combination of the above mentioned KPIs (either locally at the AP or in some core network entity) to produce additional metrics to gather insights or draw conclusions at the relative quality of the access network.

5.3. Wi-Fi Alliance™

Wi-Fi Alliance drives global Wi-Fi adoption and evolution through leadership, spectrum advocacy, and industry-wide collaboration. It includes the development of innovative technologies, requirements, and test programs that help ensure Wi-Fi provides users with the interoperability, security, and reliability they have come to expect.

5.3.1. *Wi-Fi CERTIFIED Data Elements™*

The Wi-Fi Data Elements Working Group defines a data model to describe a standardized set of Wi-Fi diagnostic parameters (aka KPIs) and configuration commands. The KPIs defined include network parameters that can be used in deciding when to transition a device to another Wi-Fi network or to another RAN, such as cellular. There are 2 main architectural components:

1. **Data Elements Agent**: It is defined as an entity which resides either on the Wi-Fi AP (in case of a standalone AP deployment) or on a EasyMesh Controller (in case of an EasyMesh deployment) which populates the data model and receives commands from a collector-controller.

2. **Data Elements Collector-Controller**: It retrieves the data from the Data Elements Agent via the Data Elements protocol.

Wi-Fi Data Elements may use any of the following management protocols such as HTTP (HyperText Transport Protocol), USP (user services platform) TR-369 or XML (Extensible Markup Language) formatted TR-181. The following are some of the KPIs that the Data Elements Agent collects and reports to the Collector-Controller; Channel scans, STA capabilities, BSS (basic service set) load information, Association events, Failed connection events, Dissociation events etc.

These KPIs could help the UE in selecting the correct network during the transition phase.

5.3.2. *Wi-Fi CERTIFIED Optimized Connectivity Experience™*

The Wi-Fi Optimized Connectivity Experience (OCE) Specification [2] describes a method for an AP to reject a (Re-)Association request from a client (UE) if the RSSI of the (Re-)Association request is below a minimum configurable threshold value, somewhere between –60 and –90 dBm. The client, upon receiving this rejection shall not attempt to (Re-)Associate until the client estimates that its (Re-)Association request will meet the requirements of the AP, sent in the rejection, or sufficient time has elapsed meeting the delay value sent by the AP in the rejection.

This method can be used to keep UEs from associating to the AP too far outside the recommended coverage area. It does not, however, help to move a UE off Wi-Fi and onto cellular data when it is at the edge of coverage.

5.3.3. *Wi-Fi CERTIFIED Agile Multiband Specification™ and Cellular Data Awareness*

The Wi-Fi Agile Multiband Specification [1] defines a method for a Wi-Fi Agile Multiband cellular data capable client (UE) and a Wi-Fi Agile Multiband cellular data aware AP to communicate the status of the UE's cellular data connection. The specification also adds the ability of the AP to recommend, sometimes strongly, that the UE transfer its data connection from Wi-Fi to the cellular network. It is still up to the UE to decide whether to follow the AP's recommendation, however, this is a good first step towards knowledge of a UE's other access networks.

Specific uses of the Wi-Fi Agile Multiband cellular capability/awareness method are:

1. To let a Wi-Fi AP know of a UE's cellular connection status, a UE may include a Cellular Data Capabilities Attribute in its Probe Request, (Re-)Association Request, and WNM-Notification Request to an AP of Connected, Not Connected, or Not Capable.

2. An AP, that wants a UE to transition to cellular data, may include the cellular data network in the Candidate List of a BSS Transition Management Request.

3. An unassociated UE asks an AP if the AP thinks the UE should use cellular data, instead of associating.

At the time of this writing, this capability is present in some APs and recent UEs today. However, we are not aware of any APs or UEs that are using this capability in the manner described in #2 or #3 above. In addition to this limitation, having a binary connected/not connected status is probably not enough for an AP to determine which network (Wi-Fi or cellular) is better for the UE to use. For this feature to be useful, we believe additional KPIs about the UE's cellular data connection would need to be shared with the AP.

5.4. Other Wi-Fi Infrastructure Solutions

Many Wi-Fi infrastructure components targeted to the enterprise, such as APs and Wireless LAN Controllers (WLC), provide features that can help clients transition off Wi-Fi when they are at the fringes of coverage. These features include:

- Minimum RSSI enforcement, like the OCE minimum RSSI for Association feature, but which can be used to disassociate clients on the fringe of coverage
- Minimum MCS rate, which essentially shrink the coverage of the AP to only allow clients to participate in areas of good signal strength

5.5. Over-The-Top solutions

OTT solutions combine multiple network connections, such as cellular and Wi-Fi, to provide improved connectivity, higher bandwidth, and seamless network transitions. These solutions often operate independently of network infrastructure, making them versatile and widely applicable. These solutions enhance the user experience and lower operating costs by providing seamless transition with IP continuity, bandwidth aggregation and efficient traffic offload across all operator networks. Some OTT solutions tunnel traffic through a VPN (encrypted or not) to maintain IP address continuity, while others do not bother with this discontinuity as many smartphone applications do a decent job of recovering from connection breaks. Some OTT solutions are meant to be deployed in a Carrier bundle while others are add-on functionality that can be compiled into an operator's brand-name application.

Server-based software only OTT solutions consist of two main components – a client in the form of a mobile SDK (software development kit) (an app or daemon) on the user terminal and a server (cloud-based) that acts as the anchor point and can be integrated into operator head-ends (north bound of the core network). The cloud server can provide analytics and manage policies to manage traffic based on operator preferences. The SDK and the server establish an IPSec tunnel across multiple access networks. While server-less OTT solutions, rely on client-side SDK to perform application-level steering by ensuring the data is sent over responsive networks that can provide the required level of QoE (Quality of Experience) for the specific user application. At the core, these OTT Apps do pretty much the same as an ATSSS capability – attempt to efficiently route traffic across available access network, with the server functionality (in case of server-based OTT solution) at the northbound of the UPF (User Plane Function) (instead of being integrated within the UPF).

5.5.1. Multipath TCP (MPTCP)

Multipath TCP (Transmission Control Protocol) is an extension of the traditional TCP protocol that enables a device to use multiple network paths simultaneously. This allows for the aggregation of bandwidth from both Wi-Fi and cellular connections.

Key Features:

- **Simultaneous Use**: Utilizes both Wi-Fi and cellular networks at the same time for increased bandwidth and reliability.
- **Seamless Handover**: Smoothly transitions between networks without interrupting active sessions.
- **Redundancy**: Provides failover capabilities, maintaining connectivity if one network fails.
- **Mobile Video Streaming**: Ensures uninterrupted streaming by combining available bandwidth.
- **Data Transfer**: Improves speed and reliability for large file transfers and cloud services.

5.5.2. SD-WAN (Software-Defined Wide Area Network)

SD-WAN (Software Defined WAN) is a virtual WAN (wide-area network) architecture that leverages any combination of transport services, including MPLS (multi-protocol label switching), LTE (long-term evolution), and broadband internet services, to securely connect users to applications.

Key Features:

- **Intelligent Path Control**: Automatically directs traffic over the best available link (Wi-Fi, cellular, etc.).
- **Application-aware Routing**: Prioritizes critical applications and optimizes their performance.
- **Security**: Provides integrated security features such as encryption and firewall capabilities.

Use Cases:

- **Remote Offices**: Ensures reliable connectivity for remote or branch offices using a mix of internet and cellular connections.
- **Business Continuity**: Maintains continuous business operations by dynamically routing traffic.

5.5.3. Bonding Solutions

Bonding solutions combine multiple internet connections, including Wi-Fi and cellular, into a single, faster, and more reliable connection. These solutions typically use specialized software or hardware.

Key Features:

- **Bandwidth Aggregation**: Combines the speed of multiple connections for increased bandwidth.
- **Failover Protection**: Automatically switches to an available connection if one fails.
- **Load Balancing**: Distributes traffic across multiple connections for optimal performance.

Use Cases:

- **Live Streaming**: Provides a stable and high-bandwidth connection for live video broadcasts.
- **Travel and Remote Work**: Ensures reliable internet connectivity for mobile workers and travelers.

5.5.4. Network Mobility Solutions

Network mobility solutions such as Mobile IP provide seamless connectivity across different networks (Wi-Fi and cellular) while maintaining the same IP address.

Key Features:

- **Seamless Roaming**: Maintains ongoing connections without interruption when switching networks.
- **Consistent IP Address**: Keeps the same IP address, which is critical for certain applications.
- **Scalability**: Suitable for large-scale deployments in enterprises and IoT environments.

Use Cases:

- **Vehicular Networks**: Ensures consistent connectivity for vehicles moving between different network zones.
- **IoT Devices**: Supports IoT devices that require uninterrupted connectivity across diverse locations.

OTT solutions offer significant advantages in terms of connectivity, bandwidth, and reliability. However, they may come with certain drawbacks. Operators need to evaluate if the benefits of implementing these solutions in the network significantly outweigh the potential downsides to make informed decisions.

1. **Complexity and Cost -** Deploying and managing OTT solutions can be complex, requiring specialized knowledge and expertise. They may incur CAPEX (capital expenditure) significant for hardware, software, and setup, as well as ongoing OPEX (operational expenditure) for maintenance and updates.

2. **Network Performance Issues** - Aggregating multiple networks can introduce latency due to the additional processing required to manage multiple connections, especially if the latency variance across the connections is high limiting the performance.

3. **Security Concerns -** Aggregating data across multiple networks can create security vulnerabilities, especially if both the networks do not implement the same level of security, while implementing robust security measures like encryption can add overhead, negatively impacting the performance benefits.

4. **Compatibility and Integration –** OTT solutions may not be supported by all devices (across different operating systems), which can limit their applicability and integrating these solutions with existing network deployments may become challenging.

5. **Battery Issues -** Continuously managing multiple connections can lead to increased battery consumption on devices.

6. **Privacy Concerns -** Ensuring data privacy when data is transmitted over various networks can be challenging, especially in regions with strict data privacy laws

7. **Vendor Lock-In** – The proprietary nature of the OTT solutions may make them less flexible or customizable and can lead to vendor lock-in making it difficult to switch providers

8. **Scalability Issues** – Scaling may require significant investment in additional infrastructure and management tools and with more connections being aggregated, managing and optimizing these connections can become increasingly challenging, potentially leading to performance bottlenecks.

5.6. OS/OEM User Preference Settings

OS vendors and OEMs have been adding features to improve, or at least affect, seamless connectivity for some time. These features are usually configurable by the user and, often, by operators. The features are named differently by each OS vendor and OEM, but generally fall into the following categories:

- Enabling the cellular radio to remain able to send and receive data while Wi-Fi is active
- More aggressively switching to cellular data when Wi-Fi quality degrades
- Enabling a power-saving mode that may reduce the Wi-Fi network scanning interval (note: may negatively affect seamless connectivity)

Some of these features are, effectively, hidden behind undocumented menus and will not be seen by most users. Others are defaulted off and so will not be used by most end-users. Some features have started as defaulting to off and/or hidden, but have since been uncovered and enabled in more recent firmware versions or UE models, as they have been proven to be effective.

6. Next Steps

Our plan is to continue testing congestion-based and mobility-based scenarios to allow more accurate characterization of the transition problem. In addition, we will work with Application vendors to gather the KPIs that they monitor, and the methods they employ to reduce the disruptions during transitions. Possible outcomes might include:

- Proposing new triggers that could provide a better understanding of the network quality which the device could leverage to trigger the transitions efficiently and dynamically across the Wi-Fi and cellular networks considering the requirements of the requested service from the user
- Defining mechanisms for the network to make these metrics available to the UE
- Recommending optimal threshold values to be used by the UE for transition points
- Proposing to implement a standardized way of transitioning devices across the Wi-Fi and cellular networks based on operator defined triggers and thresholds

Ultimately, we will attempt to work with all stakeholders in the industry to improve the user experience during network transitions, with the goal of having a solution that has as much in common across the ecosystem as possible.

In addition, there are several ongoing CableLabs projects that may have a positive impact on, and have close synergies with, seamless connectivity.

Quality by Design (QbD)

QbD is an in-house initiative at CableLabs and is a concept of Network as a Service (NaaS) that leverages a set of APIs to facilitate two-way communication between applications and the network. This approach provides true visibility into user experience by allowing applications to share real-time KPIs that can be correlated with network performance. QbD enables applications to trigger real-time KPI collections to identify potential impairments and provide automated solutions.

QbD can benefit Seamless Connectivity by correlating the network KPIs and application KPIs to provide a good indication of user experience to the network and providing more accurate representation of network quality to the devices and applications to make more informed and efficient network transitions across Wi-Fi and cellular.

Transport Protocol Analysis

Given the rise in heterogenous deployments and demanding applications such as immersive XR (extended reality), self-driving cars, and healthcare robots which require diverse and challenging QoS (Quality of Service) requirements (low latency/jitter, high data rates, etc.) network performance depends heavily on how applications, the transport layer, and the network work in synergy. Transport Protocol Analysis evaluates the multipath capabilities available in different transport protocols (such as MPTCP and

MPQUIC) and analyzes their performance benefits. The performance (throughput, latency, etc.) is measured through both emulations and real-world traffic testing, and the results are presented to help determine the use case(s) and applicability of each protocol and deployment options.

Understanding the transport protocols (such as QUIC, DCCP (datagram congestion control protocol), and SCTP (stream control transmission protocol)), their contrasting features with the legacy protocols (such as TCP and UDP (user datagram protocol) and the recent improvements in transport protocols (such as lower latency and stream multiplexing), can significantly benefit seamless connectivity across available networks.

CableLabs will continue to evaluate how these and other projects can be brought to bear on the seamless connectivity challenge.

7. Conclusion

In conclusion, the quest for seamless connectivity across Wi-Fi and cellular networks is a complex challenge being tackled by various stakeholders, including chipset manufacturers, device manufacturers, operating systems vendors, network operators, and application developers. However, the lack of a unified, standardized approach has resulted in inconsistent user experiences. Each stakeholder employs different methodologies and technologies to manage network transitions, leading to fragmentation and variability in performance. This disparity underscores the need for industry-wide collaboration and standardization to ensure reliable and uniform connectivity experiences for users, irrespective of their device or network choice.

Abbreviations

3GPP	3rd Generation Partnership Project
AP	access point
API	application programming interface
ATSSS	access traffic steering, switching, and splitting
bps	bits per second
BSS	basic service set
CAPEX	capital expenditure
COTS	commercial off-the-shelf
dBm	decibel-milliwatts
DCCP	datagram congestion control protocol
DUT	device under test
HD	high-definition
HN	home network
HTTP	hyper-text transport protocol
iOS	mobile operating system produced by Apple Corporation
IoT	internet of things
IP	internet protocol
kbps	kilobits per second
KPI	key performance indicator
LAN	local area network
LTE	Long-Term Evolution
MAC	media access control
MCS	modulation and coding scheme index
MNO	mobile network operator
MPLS	multi-protocol label switching
MPQUIC	multi-path QUIC
MPTCP	multi-path TCP
ms	millisecond
MSO	multiple systems operator
MVNO	mobile virtual network operator
NaaS	network as a service
NR	new radio
OCE	Optimized Connectivity Experience
OEM	original equipment manufacturer
OPEX	operational expenditure
OS	operating system
OTT	over-the-top
QbD	Quality by Design
QoS	quality of service
QUIC	a general-purpose transport layer protocol
RAN	radio access network
RSSI	received signal strength indicator
RTP	real-time protocol
RTT	round trip time
RX	reception
SCTE	Society of Cable Telecommunications Engineers

SCTP	stream control transmission protocol
SDK	software development kit
SDO	standard development organization
SD-WAN	software defined wide area network
SIM	subscriber identity module
SoC	system on chip
SSID	service set identifier
STA	station (Wi-Fi)
TCP	transmission control protocol
TX	transmission
UDP	user datagram protocol
UE	user equipment (Smartphone)
UMTS	Universal Mobile Telecommunications System
UPF	User Plane Function
USP	user services platform
VPN	virtual private network
WBA	Wireless Broadband Alliance
WG	working group
WLC	wireless LAN controller
WNM	wireless network management
XML	Extensible Markup Language
XR	extended reality

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7.

Appendix

Subscribers have access to multiple networks both within the home and outside. Most of the devices follow a Wi-Fi First paradigm, which ensures that the device probes and prefers to connect to a Wi-Fi network first, before connecting to a cellular network.

Figure 9 shows different stages of device connectivity from being in a stationary mode (inside a home network (HN)) to moving out of the house (with no Wi-Fi available). Consider a use case wherein there are two Wi-Fi APs (one on the first floor and the other on the main floor). The Wi-Fi STA (DUT) is stationary and is within the coverage area of the 1st floor AP. The DUT selects the HN private SSID (service set identifier) (of Wi-Fi AP1) based on multiple factors (explained later in the paper) and associates with it. After a while, as the DUT starts moving away from the coverage area of Wi-Fi AP1 and comes into the vicinity of Wi-Fi AP2, it associates with AP2.

Theoretically, the switching between the two APs should be seamless and the traffic should be uninterrupted. This type of mobility/AP-AP handover/steering, using BSS Transition Management, is covered by Wi-Fi Alliance's Agile Multiband Specification [1]. CableLabs has also developed a solution called Mobile Wi-Fi [4] to address the same issue with a much lower handover time.

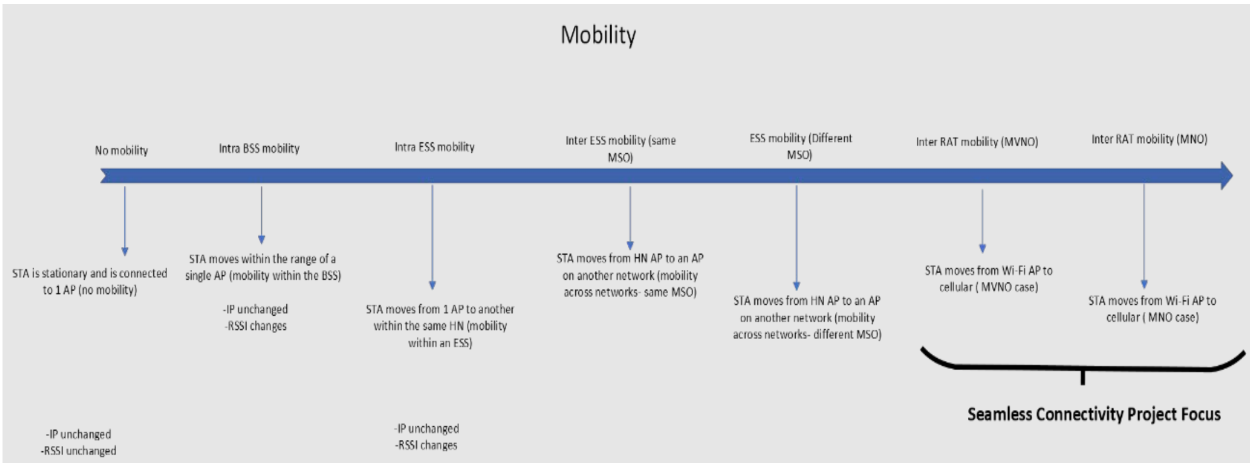

Figure 9 – Spectrum of Device Mobility: Intra-BSS through" Inter RAT

As the Wi-Fi STA moves out of coverage of the Wi-Fi AP2 (out of the house), the Wi-Fi STA probes to check for any other Wi-Fi APs nearby. The DUT would typically prefer the Community Wi-Fi SSID (that belongs to a neighbor who is a same MSO subscriber or a partner-MSO subscriber). As the device moves further away from the coverage area of any Wi-Fi signal (user walking or driving away), and if no new Wi-Fi network(s) are discovered, then the DUT transitions from Wi-Fi to cellular (mobility-based transition).

Because the network transition is initiated after a certain Wi-Fi threshold is reached (more details in upcoming sections), the device attempts to search for a better performing Wi-Fi network before transitioning to cellular data. This can result in a negative impact on the user experience during the data session. The DUT remains connected to the poor performing Wi-Fi network until the RSSI falls below a defined threshold, which causes traffic disruption.