6Rx Smartphone in 5G-NR FR1-TDD

Benefit & Deployment Recommendation

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Contents

1 Introduction: 6Rx Smartphones in 5G-NR

When 5G-NR was launched the de-facto number of smartphone receiver chains (Rx) in FR1 bands was 4Rx. Handset manufacturers are looking for differentiators for their premium products to provide better user experience over others. 6Rx in smartphones is an option to improve both coverage and user experience. From an operator's perspective, the prime FR1 bands have limited spectrum and there is strong desire to increase network capacity. Introducing 6Rx in smartphones is one way to increase network capacity by improving spectral efficiency.

1.1 Motivation for 6Rx Smartphones

There is a strong desire to increase network capacity, especially DL network capacity due to the following reasons:

- FR1 bands have limited spectrum.
- Smartphones typically use DL heavy applications, like video streaming.

With the introduction of 6Rx in smartphones, even when supporting up to 4 layers, DL spectral efficiency can be improved due to better combining gain and better interference rejection capabilities coming from 6Rx over 4Rx. 6Rx smartphones can enable up to 6 layers on DL in the future 3GPP release 19, thereby improving spectral efficiency and hence cell capacity even further.

1.2 Practical Design Considerations

To achieve higher spectral efficiency with 6Rx smartphones, the antenna placements for each Rx within the smartphone must be carefully designed. Design goals include as much antenna decorrelation between each pair of antennas as possible. This enables better diversity gain which in turn results in better spectral efficiency. When 6 layers on DL is available this also enables better 6-layer performance.

Antenna decorrelation is a function of physical antenna spacing in terms of multiple of wavelength and / or antenna polarization separation. Typically, 4 wavelengths or higher physical separation results in good antenna decorrelation and diversity gains. Folding smartphones are getting popular which when unfolded increases the smartphone surface are and makes it easier to accommodate 6Rx antennas with larger physical separation for lower antenna correlation.

Considering typical smartphone form factors and dimensions, frequency bands above 1GHz are most suitable for 6Rx operation. Frequency bands below 1GHz will require very large physical antenna separation which may not be practical in current smartphone form factor.

Another point to consider is future 6-layer support on DL; to sustain 6-layer transmissions on DL SINR requirements are significantly large. High DL SINR is most feasible in massive MIMO (M-MIMO) networks due to beamforming gains. Typical M-MIMO networks today are mostly deployed in FR1-TDD bands which are 2.5GHz to 4.0GHz range. So, FR1-TDD band smartphones will enjoy higher spectral efficiency from 6Rx due to better diversity gain / interference cancellation and up to 6-layer transmissions on DL.

1.3 3GPP Dependencies

6Rx smartphones supporting up to 4 layers on DL does not need any 3GPP version update beyond release 15. Optionally, starting with 3GPP release 17 provides UEs the ability to inform the network that it can support SRS Antenna Switching with more than 4Rx antennas. Even without the release 17 feature, smartphones can implement 6Rx transparently to the network. Future 6-layer support on DL will require 3GPP version update beyond release 18.

2 4Rx vs 6Rx Smartphones: How do they compare?

The primary difference between 4Rx and 6Rx smartphones is on the DL. UL for both smartphones can either be 1Tx (typically UL SISO or PC3 UE) or 2Tx (typically UL MIMO or either PC2 or PC1.5 UE). So, we do not expect any difference in UL performance between 4Rx and 6Rx smartphones. One exception being 6Rx UEs with Tx antenna switching diversity can mitigate the effects of hand blocking on one or more antennas better than 4Rx UEs with the same feature. Another exception being better SRS performance if 6Rx smartphones use 3GPP release 17 SRS antenna switching with more than 4Rx antennas feature.

On DL, 4Rx smartphones can support up to 4-layers and benefit from diversity gain and interference rejection gains due to 4Rx antennas whereas 6Rx smartphones currently support up to 4-layers (6-layer support in future beyond release 18) can experience higher spectral efficiency, better diversity gain and interference rejection gains due to higher number of receive chains along with interference cancellation algorithms like MMSE-IRC (Minimum Mean Square Error – Interference Rejection Combiner). With future 6-layer support, 6Rx smartphones can get up to 1.5 times higher peak DL throughput than 4Rx smartphones.

Description	4Rx UE	6Rx UE
Number of DL receive chains	4	6
Number of DL SU-MIMO layers	Up to 4 layers	Up to 4 layers (today); Up to 6 layers (future beyond 3GPP release 18)
Peak DL Throughput	1x	Up to 1.5x higher with future 6 layers
UL Performance	No difference with respect to 6Rx without UL antenna switching diversity	Can improve UL performance if 6Rx uses UL antenna switching diversity to mitigate hand blocking of antennas
SRS Performance	Same as 6Rx or worse if 3GPP Rel 17 SRS antenna switching more than 4Rx antennas enabled	Same as 4Rx or better if 3GPP Rel 17 SRS antenna switching more than 4Rx antennas enabled

Figure 2-1 4Rx vs 6Rx UE Comparison

2.1 Which channels benefit from 6 receivers in smartphones?

6Rx in smartphones should benefit all channels on DL and optionally SRS performance on UL if 3GPP release 17 SRS antenna switching more than 4Rx antennas is enabled. Apart from the obvious PDSCH channel benefits of higher SPEF due to higher number of SU-MIMO layers, better diversity gain and better interference rejection, 6Rx result in more robust DL control channel performance (PDCCH) due to better diversity gain and interference rejection. This benefit will be more evident in networks with a single broadcast beam systems (broad beam equates to higher interference for broadcast control channel). We expect higher improvement for cell-edge DL performance where interference is likely higher than cell-center.

2.2 Which applications benefit from 6Rx in smartphones?

A smartphone with 6Rx antennas is expected to consume more battery power while providing enhanced user experience than the 4Rx baseline. Due to high data demand, DL heavy applications like video streaming, FTP file transfers, speed tests, etc. will benefit most from 6Rx implementation across all radio conditions. The benefits of higher SPEF will outweigh the marginal increase in battery power consumption in a well-designed solution. More details on performance power tradeoff are provided in subsequent sections. For cell-edge users, all PDSCH applications including voice, as well as the control channels will benefit from 6Rx due to improved diversity gain and interference rejection. Intelligent management of antennas across all radio conditions and all applications should maximize benefits of 6Rx without impacting the battery life.

3 Device and Infrastructure Requirements

3.1 UE Capability Requirement

Assuming network supports up to 4-layer SU-MIMO on DL, 6Rx implementation in smartphone can be transparent to the network and unless specified otherwise, it is assumed that UE supports 4-layer SU-MIMO. If network supports more than 4-layer SU-MIMO on DL, then explicit UE-support indication is used as part of the capability message to inform gNB of its capability. The UE-capability indications defined in 3GPP to standardize the process are listed below:

- UE must be able to convey maximum SU-MIMO layers on DL per CC (*maxNumberMIMO-LayersPDSCH*). Up to release 18, only 2, 4 and 8 layers are defined in 3GPP for DL. For future releases, this information element would likely be updated to include 6 layers as well.
- Optionally, UE can support UL Tx Antenna Switching Diversity across all 6 antennas to improve UL performance due to reduction in probability of hand blocking the active Tx antenna.
- Optionally, if UE supports release 17 SRS Antenna switching for more than 4Rx, then UE must be able to convey the same to the gNB (*srs-AntennaSwitchingBeyond4RX-r17*).
- If above is true, then UE must be able to also convey a combination of supported xTyRs. (*supportedSRS-TxPortSwitchBeyond4Rx-r17 {t1r1, t2r2, t1r2, t4r4, t2r4, t1r4, t2r6, t1r6, t4r8, t2r8, t1r8}*)

3.2 gNB Infrastructure Requirement

If gNB supports up to 4-layers SU-MIMO on DL and do not support release 17 SRS Antenna switching for more than 4Rx, 6Rx implementation in the UE is transparent to the gNB. Otherwise, similar to the UE-capability, the gNB is required to support corresponding 6-layer (past release 18) and/or SRS antenna switching capabilities. Upon receipt of UE-capability-message, gNB may decide to configure the UE appropriately, which could be treated as an indirect indication of its capability to support such features.

4 Network Simulation Results: 4Rx-4L vs 6Rx-4L vs 6Rx-6L

To estimate realistic benefit of 6Rx in smartphones against a baseline of current 4Rx smartphone ecosystem, system simulations were done for both types of 4L SU-MIMO and 6L SU-MIMO, with real world dense urban site deployment, spectrum scenario and smartphone user distribution.

Three sets of comparative results as outlined below are discussed in the subsequent sections:

- All 4Rx UE's who are capable up to 4-layer SU-MIMO [Baseline].
- All 6Rx UE's who are capable up to 4-layer SU-MIMO.
- All 6Rx UE's who are capable up to 6-layer SU-MIMO.

Coverage, user experience and network capacity metrics are compared.

The assumptions we used for these simulations as well as the comparative results are presented in the following sections.

4.1 Simulation Assumptions

The simulations were performed for a cluster in a tier-1 global city, urban morphology with realistic site deployment and the following high-level details:

- 2 km^2 cluster, Urban Morphology || 38 Macro Sites || 19 sites/km^2
- 60% Outdoor Area, 40% Indoor built-up area
- Outdoor/Indoor User = 30% / 70% || Avg. 10 UE/sector
- Data Activity Factor: As per application type
- PC2 UL Tx Power
- 3.5 GHz (n78) || 100MHz BW, 30kHz SCS || 64TRX, 192AE M-MIMO || Up to 256QAM, 4 or 6L DL MIMO || 7DSUU TDD || Building Penetration Loss: 27dB
- Baseline: Smartphone with 4Rx || Simulation: Smartphone with 6Rx

Application Types

- Full-buffer Data
- Video streaming

- Cloud Gaming

4.2 Simulation Result: User Experience Benefits

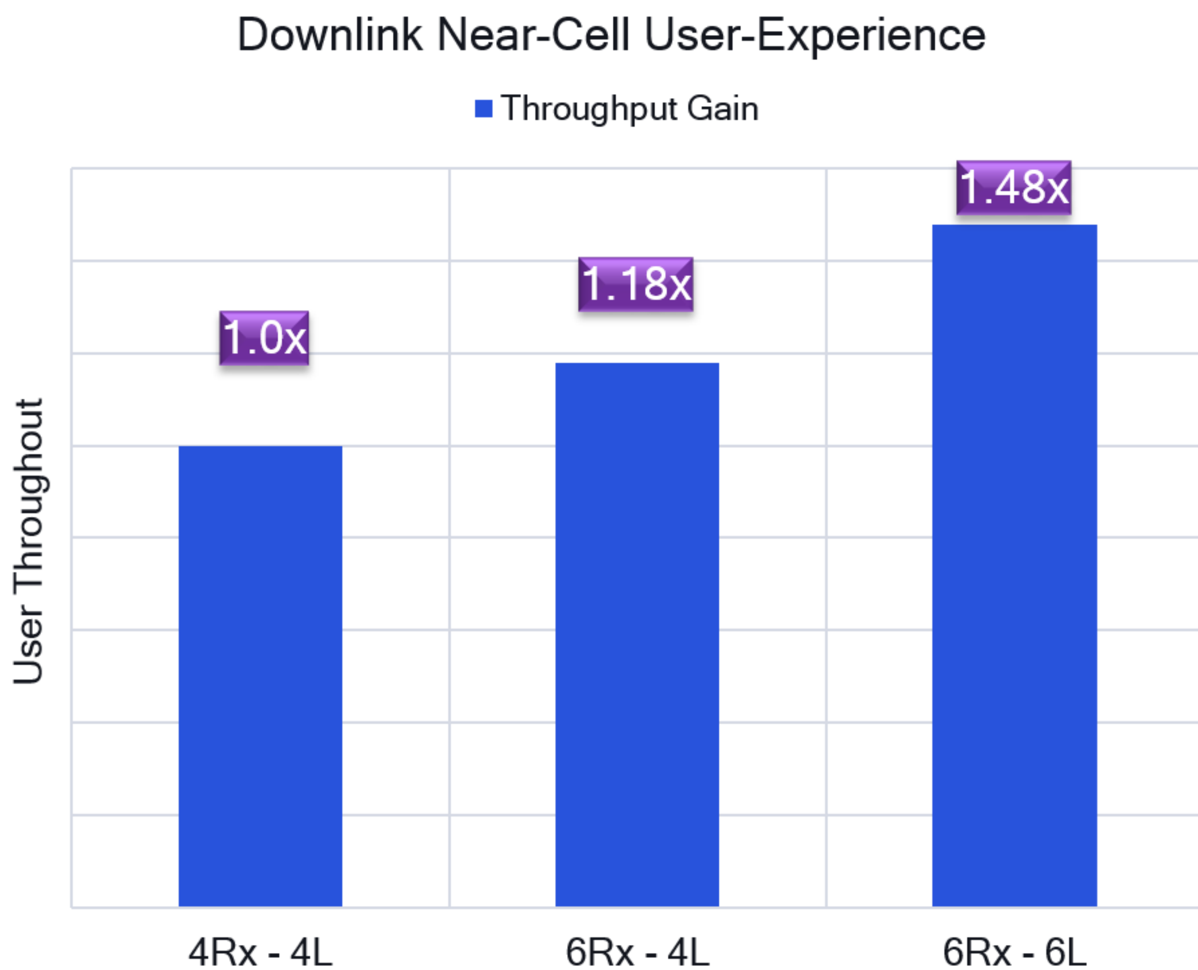

Figure 4-1 Near-Cell DL user throughput results.

Figure 4-1 Near-Cell DL user throughput results. above shows the near-cell user throughputs for all scenarios. Near-cell here represents the top 5th percentile radio condition UE, not necessarily the highest SINR condition UE. At near-cell, due to higher number of receive chains over 4Rx UEs, 6Rx UEs show up to 18% higher DL throughput. This benefit primarily stems from higher MCS and rank achieved over 4Rx UEs due to better diversity gain. When going from 6Rx-4L to 6Rx-6L, some incremental improvement seen at near-cell due to peak 6-layer SU-MIMO, which brings the overall gain for 6Rx-6L to 48% over 4Rx-4L. Note that this simulation assumes max 256QAM modulation on DL. If 1024QAM modulation is supported in DL, we would expect incrementally higher gain for 6Rx/4L UE over 4Rx/4L UE at near cell due to higher SINR, higher probability of 1024QAM with 6Rx.

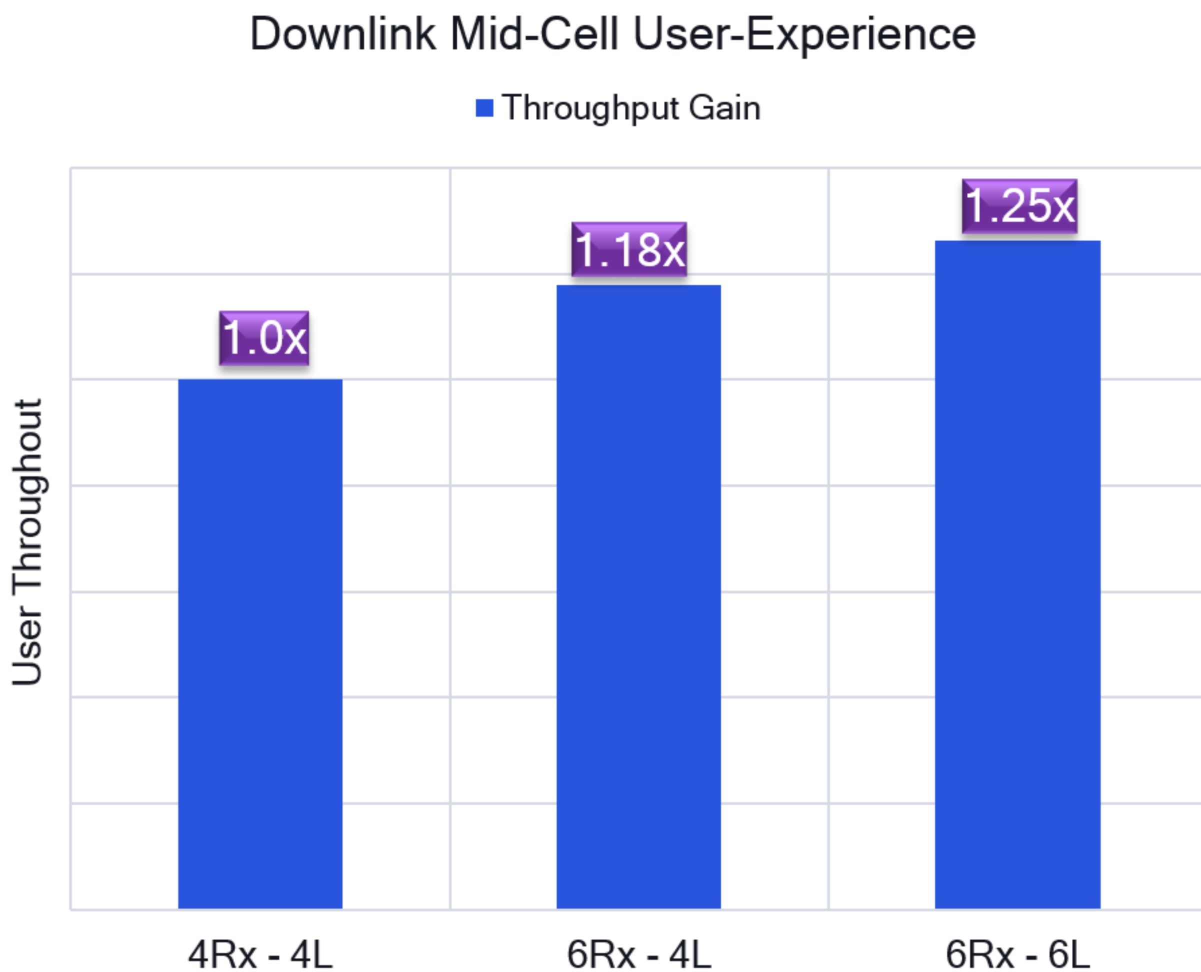

Figure 4-2 Mid-Cell DL user throughput results.

Figure 4-2 Mid-Cell DL user throughput above shows the mid-cell user throughputs for all scenarios. At mid-cell, due to higher number of receive chains over 4Rx UEs, 6Rx UEs show up to 18% higher DL throughput. This benefit primarily stems from better diversity gain and interference rejection. When going from 6Rx-4L to 6Rx-6L, some incremental improvement seen at mid-cell due to more than 4-layer SU-MIMO, which brings the overall gain for 6Rx-6L to 25% over 4Rx-4L.

4.3 Simulation Result: Coverage Benefits

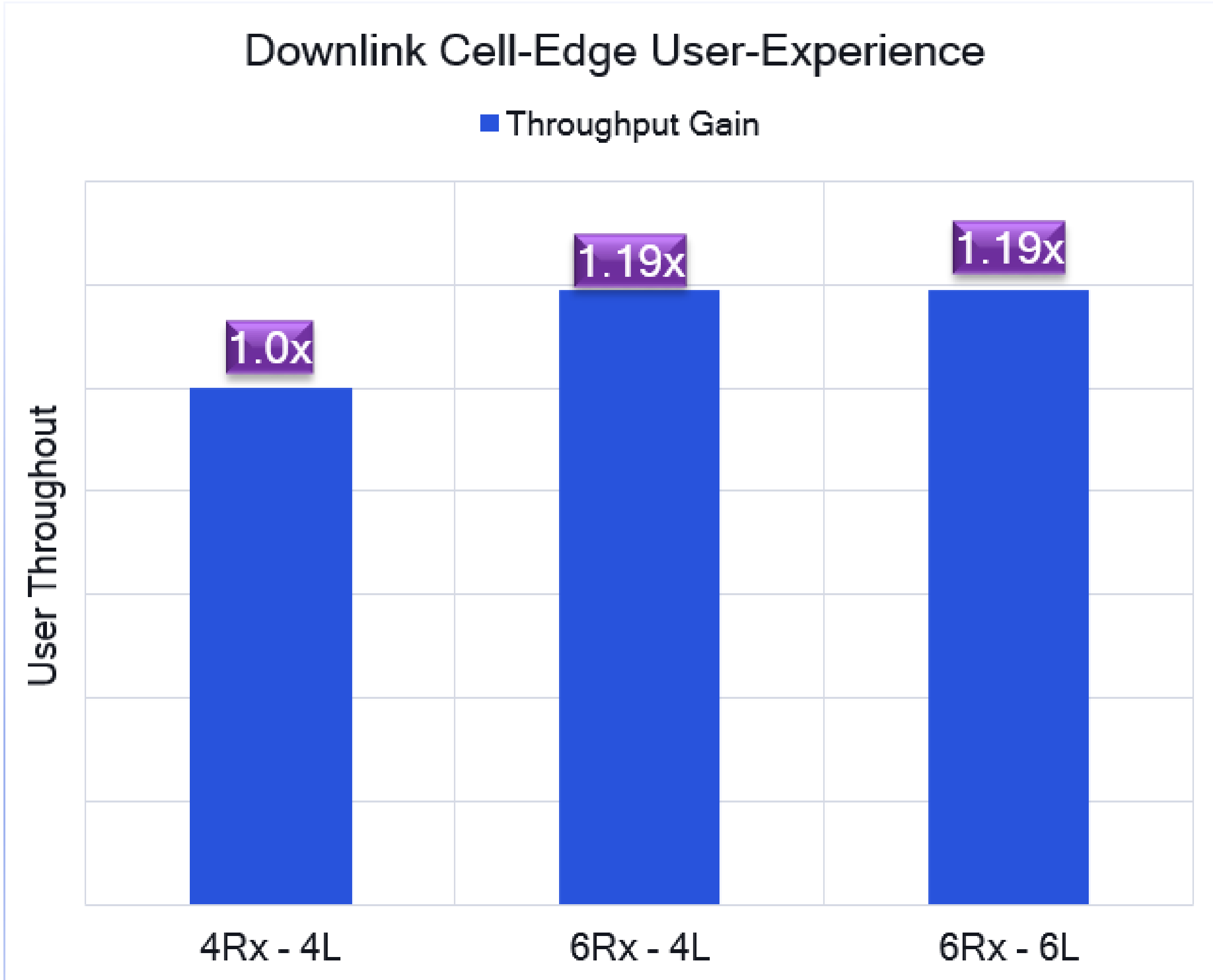

Figure 4-3 Cell-Edge DL user throughput results

Figure 4-3 Cell-Edge DL user throughput results above shows the cell-edge user throughputs for all scenarios. At cell-edge, due to higher number of receive chains over 4Rx UEs, 6Rx UEs show up to 19% higher DL throughput which can be recognized as DL coverage improvement. This benefit primarily stems from better diversity gain and interference rejection. When going from 6Rx-4L to 6Rx-6L, no incremental improvement seen at cell-edge since cell-edge users do not have enough SINR to sustain anything more than 1 SU-MIMO layer, so more layers do not bring in any advantage to cell-edge users.

4.4 Simulation Result: Network Capacity Benefits

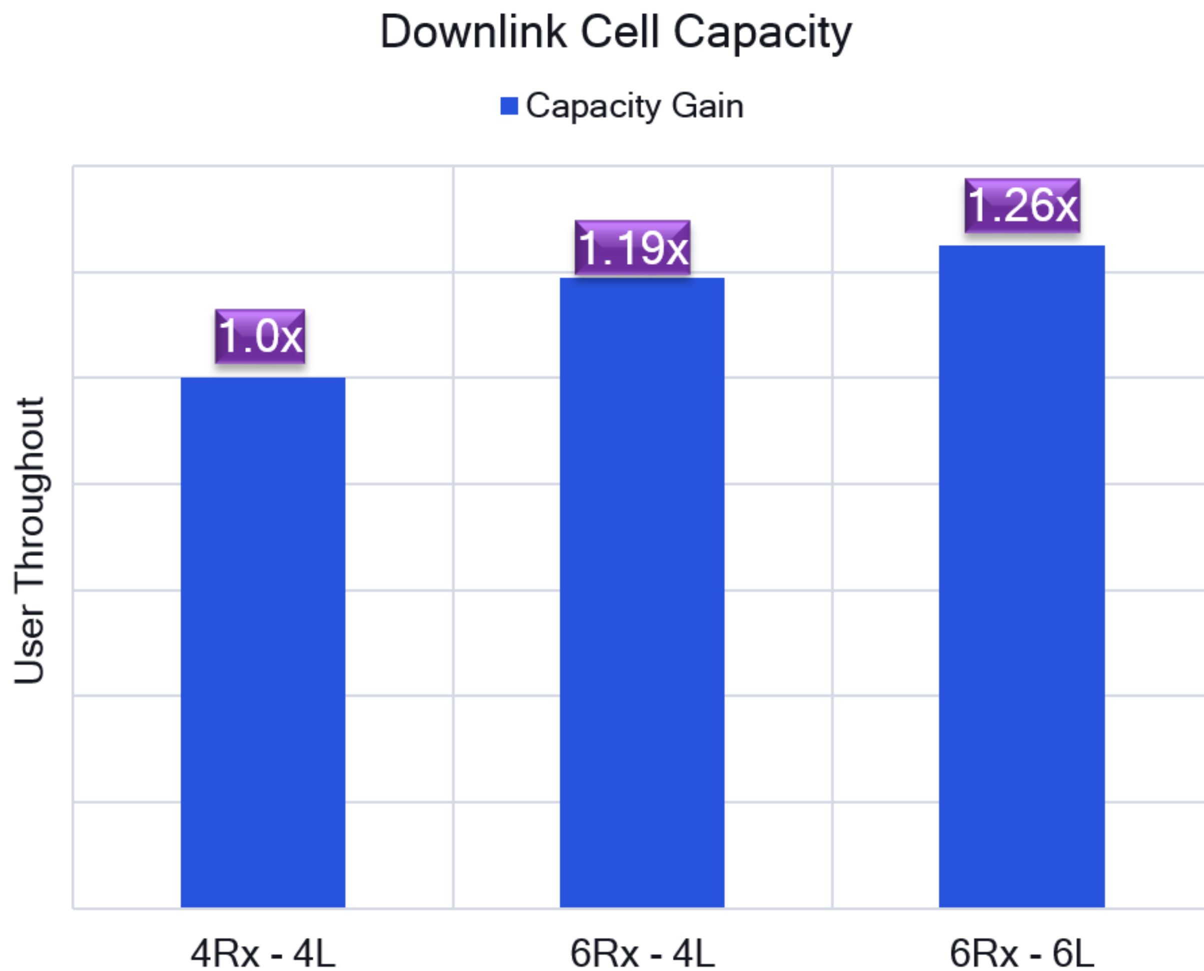

Figure 4-4 DL Average Cell Capacity results.

Figure 4-4 DL Average Cell Capacity results. above shows the average DL cell capacity assuming 100% UE penetration for each type. Overall, 6Rx-4L alone brings high about 19% higher DL cell capacity due better SPEF. Incrementally, 6Rx-6L will bring additional improvement due to higher number of SU-MIMO layers, providing 26% higher cell capacity with all 6Rx-6L UE's vs all 4Rx-4L UE's.

5 6Rx Smartphone Power Consumption vs Performance Trade-off

6Rx in smartphones is expected to provide superior user experience and lower latency over 4Rx smartphones, but also expected to consume higher battery power. In this section, we will compare the power consumption vs battery power trade-off for typical smartphone-based applications. Based on the application type, higher data rates and/or lower latency may or may not be critical for enhancing user experience. Based on the application's data rate and/or latency requirements, the smartphone modem can switch between 6Rx and traditional 4Rx modes of operation to minimize battery power consumption.

5.1 Power Consumption Simulations

This section shows simulation results for various applications' latency and battery consumption deltas for 4Rx and 6Rx UEs. Battery consumption deltas pertain to modem-RF only, does not include battery impact due to display. The simulations were performed with realistic network assumptions with following high-level details:

Network Configuration

Baseline Configuration (4Rx Smartphone)

- CDRX: 100ms (Inactivity)-10ms (On)-160 ms (Long-DRX)
- SCS: 30 KHz || TDD-Config: 7DSUU || #CC: 1CC 100 MHz
- RF Condition: Mid-cell (stationary) || Far-cell (Stationary)
- BWP Config: BWP1 (20MHz), BWP2 (100MHz)
- Network loading: Typical (Medium)

6Rx Smartphone Configuration

- All assumptions pertaining to network configuration are same as baseline

Application Type

- Video streaming
- Web Browsing
- Days of Use (DoU) – typical mix of voice, video, web-browsing, social media apps, audio streaming, etc. Assumes ~50% time in RRC connected mode and ~50% time in RRC idle mode.

5.2 Simulation Result: Video Streaming [YouTube 4K Video]

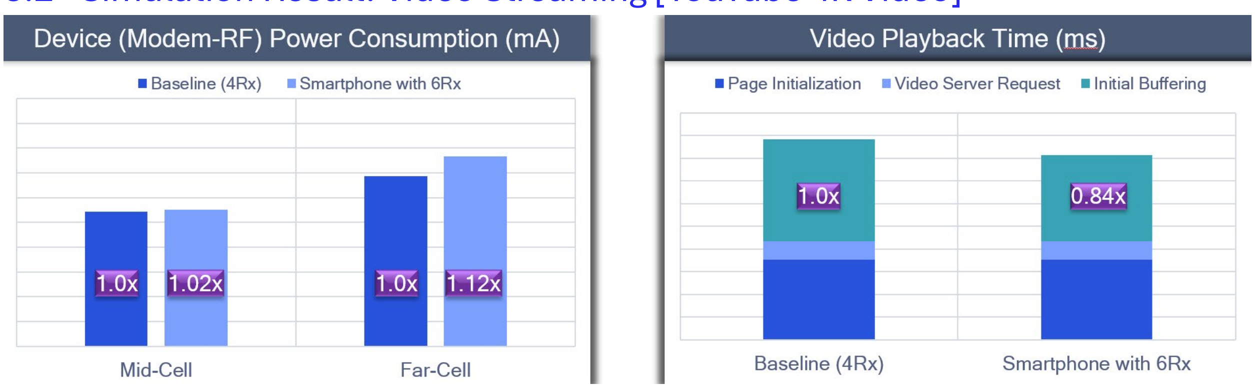

Figure 5-1 Video Streaming Modem Power Results / Latency Results at Cell-Edge

Figure 5-1 Video Streaming Modem Power Results / Latency Results at Cell-Edge above shows marginal increase in device power consumption, relatively higher at cell-edge. This increase more than offsets the performance benefits which shows significant improvement in video playback time (initial buffering) for cell-edge users.

5.3 Simulation Result: Web-Browsing Application

Figure 5-2 Web-Browsing Application Modem Power / Latency Results at Cell-Edge

Figure 5-2 Web-Browsing Application Modem Power / Latency Results at Cell-Edge above shows marginal increase in device power consumption, even for the worst-case cell-edge scenario. Benefit shows in measurable improvement in page download time which is even more prominent for successive downloads.

5.4 Simulation Result: Days of Use [DoU]

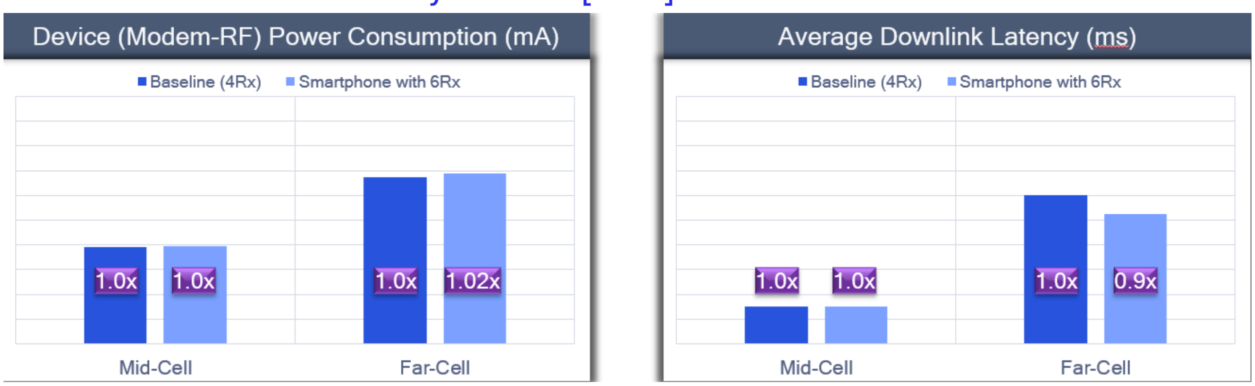

Figure 5-3 Days of User [DoU] Modem Power / Latency Results

Figure 5-3 Days of User [DoU] Modem Power / Latency Results above shows marginal increase in device power consumption, even for the worst-case cell-edge scenario. DoU represents mix of applications typically used by average user. The benefit shows as a measurable improvement in average DL air interface latency.

6 Deployment Recommendation

6Rx in smartphones will provide superior DL data rates, lower latencies and in turn also improve over DL cell capacity. Cell level benefits is a function of 6Rx smartphone penetration ratio. Most smartphone applications are DL heavy applications and will benefit from 6Rx. The benefit stems from better receiver diversity gain and better interference rejection which in turn improves SINR and SPEF. Most FR1 bands above 1GHz will benefit from 6Rx in smartphones. Due to larger wavelength and antenna size, antenna spacing requirement FR1 bands below 1GHz will be challenging to implement 6Rx in today's smartphone form factor / dimensions. Expedite deployment of 6Rx in smartphones in FR1 bands above 1GHz, followed by roll-out of 6-layer SU-MIMO on DL in the network, especially for M-MIMO networks where high SINR required for 6-layers is achievable. The UE should enable 6Rx mode of operation for most cell-edge users, and all users for delay sensitive applications or when cell loading is high. Otherwise, the UE should switch back to 4Rx mode to save battery power consumption associated with 6Rx mode of operation.

7 Conclusion

6Rx in smartphones improves downlink coverage and will sustain higher data-rates for all users. It is suitable for superior user-experience which requires higher data-burst rate and faster service time (lower latency). The higher the penetration of 6Rx smartphones in the network, the higher is the downlink network capacity. The benefits improve further with the introduction of 1024QAM and future 6-layer SU-MIMO on DL.

6Rx smartphones show marginal increase in overall modem-RF power consumption. Depending on RF conditions, far-cell may result in relatively higher power consumption. Depending on the application type, high data-rate & low-latency apps may consume relatively more power. Overall power consumption also depends on network configuration like BWP, and parameter setting like CDRX and UE Rx mode switching between traditional 4Rx mode of operation to 6Rx mode of operation.

We recommend faster and aggressive adoption of 6Rx smartphone, to improve coverage, capacity, and user-experience. We also recommend prioritizing 6Rx usage for video-streaming, gaming, voice, which are high demand and/or latency sensitive applications. Intelligent management of antennas should maximize benefits of 6Rx across all radio conditions and all applications without impacting the battery life.

References

3GPP TS 38.211 NR; Physical channels and modulation
3GPP TS 38.214 NR; Physical layer procedures for data
3GPP TS 38.306 NR; User Equipment (UE) radio access capabilities
3GPP TS 38.311 NR; Radio Resource Control (RRC); Protocol specification

Abbreviations

3GPP – 3rd Generation Project Partnership (www.3gpp.org)
BWP – Bandwidth Part
CDRX – Connected mode Discontinuous Reception
DoU – Days of Use
FDD – Frequency Division Duplexing
gNB – 5G NR NodeB (the 5G NR base station)
MMSE-IRC – Minimum Mean Square Error - Interference Rejection Combiner
PDCCH – Physical Downlink Control Channel
PDSCH – Physical Downlink Shared Channel
RRC – Radio Resource Control

SPEF – Spectral Efficiency
SRS – Sounding Reference Signal
SU-MIMO – Single User Multiple Input Multiple Output
TDD – Time Division Duplexing
UE – User Equipment (the cellphone, cellular IoT device, …)