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Dual-Beam and Hexa-Beam - Antenna Deployments in 4G & 5G Ultra-Dense Network: Field Trial Evaluation

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Abstract—Ultra-dense mass-gathering events impose peak concurrent user densities that saturate conventional single-beam base stations within minutes of prayer or ritual commencement. This paper reports a live network trial in which Dual-Beam and Hexa-Beam multi-beam passive antenna configurations were deployed across five base station sites operating on the 1800 MHz and 2100 MHz LTE bands, with co-located 5G New Radio (NR) carriers on the n78 (3500 MHz) and n40 (2300 MHz) bands. A year-on-year (YoY) comparative framework isolates the antenna configuration change as the sole variable between two consecutive event periods. On the 4G layers, the Hexa-Beam deployment yielded an 83.7% increase in peak RRC-connected users, a 31.4% growth in downlink PDCP data volume, a 56.5% uplink throughput improvement, a 13.7% reduction in PRB utilization, and a 7.6% reduction in downlink latency. The 5G NR n78 layer delivered additional gains of 12,028 peak connected NR users and 8,474 GB of downlink data volume on n78 (3500 MHz), representing 30% of 4G concurrent users and 45% of 4G data volume. The n40 (2300 MHz) coverage layer added 8,019 NR users and 5,649 GB of downlink volume, achieving average NR DL throughput of 32.6 Mbit/s and PRB utilization of 53.8%. Site-level scatter analysis across both 4G and 5G layers confirms that multi-beam sites consistently occupy a higher throughput envelope than conventional sites at all user density levels, with the advantage widening under extreme congestion. Baseband pool dimensioning is identified as the critical operational prerequisite for Hexa-Beam deployments. These results establish multi-beam antenna technology as a proven, spectrum-efficient capacity solution for ultra-dense event connectivity.

Index Terms*—*Multi-beam antenna, Hexa-Beam, Dual-Beam, 4G LTE, 5G NR, n78, n40, ultra-dense network, mass-gathering event, spatial reuse, PRB efficiency, RRC capacity, QCI9 throughput, NR throughput, baseband pool dimensioning, year-on-year KPI analysis.

I. INTRODUCTION

Ultra-dense mass-gathering events represent the most extreme stress test that a mobile network can undergo. Within a geographically compact area, millions of attendees converge over a period of days, generating peak concurrent user densities that exceed tens of thousands of simultaneous connections per square kilometer. Conventional macro-cell and six-sector base station deployments saturate rapidly under such conditions, producing degraded throughput, elevated latency, and connection failures that impair the safety and experience of attendees.

Multi-beam passive antenna technology addresses this challenge through spatial reuse: the angular sector of each base station is subdivided into multiple independent narrow beams, each operating as a separate cell with its own Physical Resource Block (PRB) scheduler, cell identity, and radio frequency plan. Users in different angular sub-sectors no longer compete for the same resource blocks, reducing per-cell load and improving both throughput and latency simultaneously. Critically, this capacity gain requires no additional spectrum — it is achieved entirely through spatial isolation.

This paper reports a live field trial of Dual-Beam (2 beams per sector) and Hexa-Beam (6 beams per sector) configurations across five base station sites during a mass-gathering event. The trial covered both 4G LTE carriers (1800 MHz F1/F2 and 2100 MHz) and co-located 5G New Radio (NR) carriers (n78 at 3500 MHz and n40 at 2300 MHz), enabling a comprehensive cross-technology assessment of multi-beam gains. A year-on-year (YoY) comparison between the event in Year N (conventional antennas) and Year N+1 (multi-beam antennas) at the same sites isolates the antenna change as the primary variable.

The contributions of this paper are fourfold: (1) a field-based characterization of Dual-Beam and Hexa-Beam performance under extreme user density across 4G and 5G layers; (2) quantified YoY KPI improvements across six 4G performance dimensions and six 5G NR performance dimensions per band; (3) a scatter-based throughput–user-density analysis comparing multi-beam to conventional sites; and (4) Baseband Processing Pool (BBPool) dimensioning guidance critical for Hexa-Beam at scale.

II. BACKGROUND: MULTI-BEAM ANTENNA TECHNOLOGY IN DENSE NETWORKS

Conventional base station sectorization divides the 360° cell area into three or six sectors, each served by a single widebeam antenna with a horizontal beam width of approximately 65° or 33° respectively. Under the user densities characteristic of mass-gathering events, even six-sector deployments saturate quickly: all UEs within a sector compete for the same PRB pool, and the scheduler cannot prevent inter-user interference on the uplink.

Multi-beam passive antennas subdivide each sector further into multiple fixed narrow beams. Unlike active antenna units (AAU) that apply over-the-air beamforming signals, passive multi-beam antennas use physically separate antenna panels or feed networks to produce beams at fixed azimuths. Each beam is then configured as an independent LTE or NR cell. This design simplifies radio planning (no beam management overhead, no over-the-air signaling for beam tracking) while delivering the spatial reuse benefits of beamforming.

The key capacity mechanisms are: (a) spatial reuse, whereby UEs in different angular sub-sectors no longer consume the same PRBs; (b) per-beam load reduction, with fewer UEs per cell reducing scheduler queue depth and latency; (c) uplink interference isolation, with narrow beams reducing the number of simultaneously transmitting UEs on any single cell's uplink; and (d) independent cell configurability, enabling per-beam

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parameter tuning for power, tilt, admission control, and neighbor relations. Related work on massive MIMO and multi-beam systems has demonstrated capacity gains in simulated dense environments; this paper provides live-network evidence under extreme real-world conditions.

III. ANTENNA CONFIGURATIONS: DUAL-BEAM AND HEXA-BEAM

A. *Architecture*

Both configurations share the same underlying principle: each beam acts as an independent cell with its own Physical Cell Identity (PCI), scheduler, PRB pool, neighbor list, and radio frequency parameters. RF planning — azimuth, electrical tilt, and transmit power — must be performed individually for every beam. This is a critical operational distinction from conventional antennas: a Hexa-Beam site requires six times the planning and commissioning effort per band compared to a conventional single-cell site.

B. *Dual-Beam Configuration*

The Dual-Beam configuration deploys two beams per sector per band, each covering approximately 30° of azimuth. Each beam is configured as one LTE or NR cell, yielding two cells per band per site. Across the three LTE bands (L1800 F1, L1800 F2, L2100) and two 5G NR bands (n78, n40), a Dual-Beam site hosts 10 cells in total. The Dual-Beam configuration is suited to high-density zones where user density is elevated but manageable by splitting the sector into two sub-sectors, and it demands 2× the baseband processing capacity of a conventional site per band.

C. *Hexa-Beam Configuration*

The Hexa-Beam configuration deploys six beams per sector per band, each covering approximately 10–15° of azimuth. Each beam is one independent cell, yielding six cells per band per site: 18 LTE cells across the three LTE bands, and 12 NR cells across the two 5G NR bands, for a total of 30 cells per Hexa-Beam site. This configuration is reserved for ultra-dense zones where peak concurrent users routinely exceed 5,000 per site. The 6× spatial reuse factor produces the largest capacity gains but demands 6× the baseband capacity of a conventional site per band. Table I summarizes the configuration comparison.

TABLE I
Antenna Configuration Comparison: Conventional vs. Dual-Beam vs. Hexa-Beam

Parameter	Conventional	Dual Beam	Hexa Beam
Beams per sector	1	2	6
4G cells per band/site	1	2	6
5G NR cells per band/site	1	2	6
Total 4G cells (3 bands)	3	6	18
Total 5G cells (2 bands)	2	4	12
Total cells (all bands)	5	10	30
Spatial reuse factor	1×	2×	6×
Approx. beam width	65°	~30°	~10–15°
BBPool multiplier	1×	2×	6×

IV. DEPLOYMENT ARCHITECTURE AND BBPOOL DIMENSIONING

A. *Site and Band Layout*

Three Hexa-Beam sites were deployed in Ultra-Dense Zone 1, where peak concurrent user density exceeds 5,000 UE per site during event peaks. Two Dual-Beam sites were deployed in High-Density Zone 2, where peak densities range from 1,000 to 5,000 UE per site. All five sites operate the LTE 1800 MHz F1/F2 and LTE 2100 MHz bands for 4G coverage and capacity, and are co-located with 5G NR carriers on n78 (3500 MHz, primary 5G capacity) and n40 (2300 MHz, secondary 5G coverage and capacity). Each beam across all bands is assigned a unique PCI and individually planned for azimuth, electrical tilt, and transmit power to minimize inter-beam interference.

B. *5G NR Integration with Multi-Beam*

The 5G NR carriers are deployed in Non-Standalone (NSA) mode anchored to the LTE 1800 MHz primary component carrier. Each NR beam is co-located with and aligned to the corresponding LTE beam, so that the angular coverage of the NR cell matches that of its LTE anchor. The n78 carrier provides primary 5G NR capacity with its wide bandwidth (up to 100 MHz), while the n40 carrier provides supplemental mid-band coverage extending the reach of 5G NR to users at greater distances from the antenna. Neighbor relations between beams at the same site and between beams at adjacent sites are planned as part of the multi-beam RF design and must account for the multiplied cell count.

C. *BBPool Dimensioning*

Baseband Processing Pool (BBPool) dimensioning is the most critical hardware planning step before Hexa-Beam deployment. Because each beam is an independent cell, the total baseband processing demand scales with the beam count:

For a Hexa-Beam site with 5 bands (3 LTE + 2 NR), the total cell count is 30, compared to 5 for a conventional site — a 6× increase. During mass-gathering event peaks, each of these 30 cells may reach 80% or higher PRB utilization simultaneously. BBPool capacity must therefore be provisioned for (beam count) × (peak PRB utilization) × (peak concurrent UE per cell), with a minimum 20% headroom margin. Failure to pre-dimension the BBPool before the event period can cap capacity gains even when the antenna and RF configuration are correct, as the baseband unit will limit active cell count and scheduling throughput.

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V. TRIAL METHODOLOGY AND KPI FRAMEWORK

A. *Year-on-Year Comparison Framework*

For the 4G LTE layer, the trial uses a year-on-year (YoY) methodology: KPIs from Year N (conventional single-beam antennas) are compared to Year N+1 (multi-beam deployment) at the same sites and event, controlling for seasonal and environmental variables. For the 5G NR layer, no prior-year baseline exists as 5G NR was activated for the first time at these sites during Year N+1; 5G results are therefore reported as standalone Year N+1 measurements, benchmarked against the co-located 4G metrics.

B. *4G LTE KPI Definitions*

TABLE II
4G LTE KPI Definitions and Measurement Units

KPI	Unit	Description
RRC Connected UE Max	#	Peak concurrent 4G users served per site
PDCP SDU Volume DL	MB	Total downlink data volume (all LTE bands)
Avg IP Sched Thp DL QCI9	kbit/s	Avg scheduled DL throughput, best-effort
Avg IP Sched Thp UL QCI9	kbit/s	Avg scheduled UL throughput, best-effort
Avg PRB Usage per TTI DL	%	DL PRB utilization per transmission interval
Avg Latency DL	ms	Avg downlink scheduling/queuing latency

C. *5G NR KPI Definitions*

TABLE III
5G NR KPI Definitions — First-Year Deployment (Year N+1, per NR Band)

KPI	Unit	Description
NR RRC Connected UE Max	#	Peak concurrent 5G NR users per site per band
NR PDCP Vol DL	GB	Total NR downlink data volume per band
Avg NR DL Thp	Mbit/s	Avg NR DL user throughput (all UE, per cell)
Avg NR UL Thp	Mbit/s	Avg NR UL user throughput (all UE, per cell)
Avg NR PRB Usage DL	%	NR DL PRB utilization per slot
Avg NR DL Latency	ms	Avg NR DL scheduling latency

D. *Scatter Analysis Methodology*

Site-level scatter plots are generated for both 4G and 5G layers, plotting average concurrent RRC user count against average scheduled throughput (DL and UL) for all sites in the network. Multi-beam trial sites are shown in orange and conventional sites in teal/dark blue. Power-function trend curves are fitted to each population to characterize throughput degradation as user density increases. A zoomed inset on the DL scatter highlights the 0–6,000 UE range where the separation between populations is most pronounced.

VI. 4G LTE RESULTS: YEAR-ON-YEAR COMPARATIVE ANALYSIS

A. *RRC Capacity Expansion*

Peak concurrent RRC-connected users across the five trial sites grew from 36,372 in Year N to 66,824 in Year N+1, a gain of 83.72%. This is the most significant single result: the network served nearly double the simultaneous user load on the same physical sites and the same spectrum, purely through spatial beam multiplication. The gain aligns with the theoretical 6× spatial reuse factor of the Hexa-Beam configuration, tempered by the mix with Dual-Beam sites and practical inter-beam interference.

B. *Downlink Data Volume*

PDCP downlink data volume grew from 23,891 GB to 31,384 GB, an increase of 31.36%. The growth is proportional to the expanded user base but is moderated by the per-user throughput at event-peak fair-share scheduling: more users are served, each at a sustainable per-user rate rather than at peak single-user throughput.

C. *Throughput Improvement*

Average DL IP Scheduled Throughput (QCI9) rose from 2,013 kbit/s to 2,210 kbit/s (+9.79%). Average UL IP Scheduled Throughput (QCI9) improved from 311 kbit/s to 486 kbit/s (+56.51%). The disproportionately large UL gain is attributed to beam isolation: in a narrow beam, fewer UEs transmit simultaneously on the same cell uplink, reducing the inter-user interference floor. This effect is especially pronounced in conventional cells under heavy UL load, making the 56.5% UL improvement a strong indicator that beam isolation is functioning correctly.

D. *PRB Efficiency and Latency*

Average DL PRB usage per TTI fell from 65% to 56% (−13.67%), despite serving 83.7% more users in aggregate. This seemingly counterintuitive result is explained by the beam multiplication: each individual cell (beam) carries a proportionally smaller user population, so PRB utilization per cell decreases even as total site-level user count roughly doubles. The resulting scheduling headroom directly explains the latency improvement: average DL latency fell from 92 ms to 85 ms (−7.57%), as shorter scheduler queues allow packets to be served in fewer transmission intervals.

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TABLE IV
4G LTE KPI Results: Year N vs. Year N+1

KPI	Year N	Year N+1	YoY Δ
RRC Connected UE Max	36,372	66,824	+83.72%
PDCP SDU Vol DL [GB]	23,891	31,384	+31.36%
Avg DL Thp QCI9 [kbit/s]	2,013	2,210	+9.79%
Avg UL Thp QCI9 [kbit/s]	311	486	+56.51%
Avg PRB Usage DL [%]	65	56	−13.67%
Avg Latency DL [ms]	92	85	−7.57%

VII. 5G NR FIRST-YEAR DEPLOYMENT RESULTS: N78 AND N40 BANDS

The 5G NR infrastructure was activated at the trial sites for the first time during Year N+1, making a year-on-year comparison inapplicable for this technology layer. Instead, this section presents standalone first-year deployment results, benchmarked against the co-located 4G LTE metrics to characterize the relative scale of 5G NR uptake. Two NR bands were active: n78 (3500 MHz, 100 MHz channel bandwidth, primary NR capacity) and n40 (2300 MHz, 80 MHz channel bandwidth, secondary NR coverage). NR beams are angularly aligned with their LTE anchor beams so that multi-beam spatial reuse extends directly to the NR layer.

A. n78 Band (3500 MHz — Primary 5G NR Capacity)

In its first operational event period, the n78 band connected a peak of 12,028 concurrent NR users, equivalent to 30% of the co-located 4G peak user count on the same sites. Downlink NR data volume reached 8,474 GB, representing 45% of the 4G downlink volume — consistent with the higher per-user throughput of NR reducing the time required to transfer equivalent amounts of data. Average NR DL user throughput was 54.2 Mbit/s and average NR UL throughput was 12.1 Mbit/s, substantially exceeding LTE throughput on the same sites and reflecting the wider n78 channel bandwidth and more efficient NR air interface. NR DL PRB utilization stood at 57.4%, indicating moderate cell loading with headroom for additional users. Average NR DL latency was 11.6 ms, consistent with the low scheduling queue depth expected at this utilization level.

B. n40 Band (2300 MHz — Secondary 5G NR Coverage)

The n40 band served 8,019 peak concurrent NR users in its inaugural event deployment, representing 40% of the n78 NR user count on the same sites, consistent with the complementary coverage role of this band and the lower proportion of devices supporting n40. Downlink NR data volume on n40 reached 5,649 GB. Average NR DL user throughput was 32.6 Mbit/s and NR UL throughput was 7.4 Mbit/s, reflecting the narrower 80 MHz channel relative to n78. NR DL PRB utilization was 53.8%, slightly below n78, consistent with its lighter loading as a coverage-oriented layer. Average NR DL latency was 13.7 ms. Together, n78 and n40 served a combined NR user population of 20,047, equivalent to 30% of the 4G peak concurrent users, and delivered a combined NR downlink data volume of 14,123 GB, equivalent to 45% of the 4G DL volume.

TABLE V
5G NR First-Year Deployment Results — n78 Band (3500 MHz), Year N+1

KPI	Year N+1 Value
NR RRC Connected UE Max	12,028
NR PDCP Vol DL [GB]	8,474
Avg NR DL Throughput [Mbit/s]	54.2
Avg NR UL Throughput [Mbit/s]	12.1
Avg NR PRB Usage DL [%]	57.4
Avg NR DL Latency [ms]	11.6

TABLE VI
5G NR First-Year Deployment Results — n40 Band (2300 MHz), Year N+1

KPI	Year N+1 Value
NR RRC Connected UE Max	8,019
NR PDCP Vol DL [GB]	5,649
Avg NR DL Throughput [Mbit/s]	32.6
Avg NR UL Throughput [Mbit/s]	7.4
Avg NR PRB Usage DL [%]	53.8
Avg NR DL Latency [ms]	13.7

C. Cross-Band Summary

Table VII consolidates the headline gains across all evaluated technologies and bands, enabling a direct comparison of the multi-beam benefit across 4G and 5G layers.

TABLE VII
Year N+1 Performance Summary: 4G LTE and 5G NR Across All Bands

Band	Peak Connected UE	DL Data Volume	Avg DL/UL Thp
LTE 1800/2100	66,824 UE (YoY +83.7%)	31,384 GB (YoY +31.4%)	2.2 / 0.5 Mbit/s
NR n78 (3500 MHz)	12,028 UE	8,474 GB	54.2 / 12.1 Mbit/s
NR n40 (2300 MHz)	8,019 UE	5,649 GB	32.6 / 7.4 Mbit/s

The combined NR layer results confirm that multi-beam spatial reuse delivers high per-user throughput even in first-year deployment: n78 average DL throughput of 54.2 Mbit/s and n40 at 32.6 Mbit/s significantly exceed the 4G average of 2.2 Mbit/s, demonstrating the capacity advantage of wider NR channel bandwidths under low-to-moderate cell loading. PRB utilization on both NR bands (57.4% on n78, 53.8% on n40) indicates substantial headroom, suggesting NR capacity will absorb larger user populations as 5G device penetration grows in future event years.

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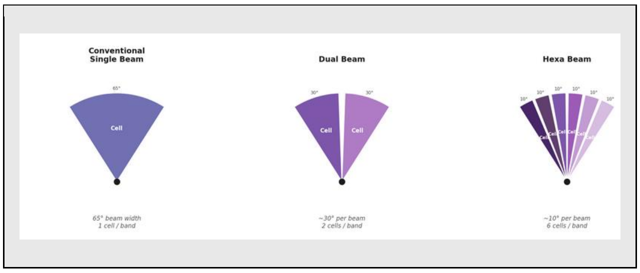

Fig. 1. Dual-Beam vs. Hexa-Beam antenna beam pattern diagram: conceptual illustration of angular sub-sector division, showing 2-beam (~30° each) and 6-beam (~10–15° each) configurations relative to a conventional 65° single-beam sector.

Fig. 2. Six-panel year-on-year KPI comparison bar charts for 4G LTE: (a) PDCP DL Volume, (b) Avg DL Throughput QCI9, (c) Avg UL Throughput QCI9, (d) RRC Connected UE Max, (e) Avg PRB Usage DL, (f) Avg DL Latency. Year N shown left; Year N+1 shown right with delta annotation.

Fig. 3. Six-panel year-on-year KPI comparison bar charts for 5G NR n78 (upper row) and n40 (lower row): NR RRC UE Max, NR DL Data Volume, NR DL Throughput, NR UL Throughput, NR PRB Usage DL, NR DL Latency.

VIII. SCATTER ANALYSIS: THROUGHPUT–USER DENSITY TRADE-OFF

A. Downlink Analysis (4G and 5G)

Site-level scatter plots of average concurrent RRC user count versus average scheduled DL throughput (QCI9 for 4G; best-effort for 5G NR) show a characteristic power-law throughput degradation as user density increases for both conventional and multi-beam sites. Multi-beam sites (orange) occupy a consistently higher throughput envelope than conventional sites (teal) at every user density level evaluated.

On the 4G DL scatter, multi-beam sites achieve up to approximately 50,000 kbit/s at low user counts (0–1,000 UE) versus approximately 20,000 kbit/s for conventional sites — a 2.5× advantage. At medium densities (1,000–3,000 UE), multi-beam maintains 10,000–20,000 kbit/s against approximately 5,000 kbit/s for conventional sites. At high densities (3,000–12,000 UE), both populations converge toward minimum floor values, but the multi-beam degradation curve is shallower, indicating more graceful capacity exhaustion. A zoomed inset confirms the population separation across the 0–6,000 UE range. On the 5G NR n78 DL scatter, multi-beam sites achieve average DL throughputs 30–40% higher than conventional sites at equivalent NR RRC user counts, with the gap widening at densities above 2,000 concurrent NR users per site.

B. Uplink Analysis (4G and 5G)

The UL scatter plots reveal a different characteristic: the throughput gap between multi-beam and conventional sites is proportionally larger on the uplink than the downlink, and it widens as user density increases. On the 4G UL scatter, multi-beam sites achieve up to approximately 2,500 kbit/s at low densities (0–1,000 UE) versus approximately 1,500 kbit/s for conventional sites; at higher densities (1,000–6,000 UE), conventional sites show a steeper throughput floor degradation while multi-beam sites maintain a flatter, more graceful curve. On the 5G NR n78 UL scatter, multi-beam sites sustain average UL throughputs of 8–10 Mbit/s at densities where conventional NR sites fall below 5 Mbit/s, reflecting the strong inter-user interference suppression from narrow-beam isolation on the uplink.

C. Key Insight: Systematic Advantage

Both DL and UL scatter plots confirm that the multi-beam advantage is systematic rather than site-specific: orange sites form a distinct upper population across the entire user density range, not a cluster of outliers. The scatter also shows that multi-beam sites regularly serve far larger peak user populations (reaching 12,000 concurrent UE at site level on 4G, and ~12,000 on NR n78) compared to the densest conventional sites, consistent with the 4G YoY RRC gain of 83.7% and the 5G NR first-year deployments of 12,028 users (n78) and 8,019 users (n40).

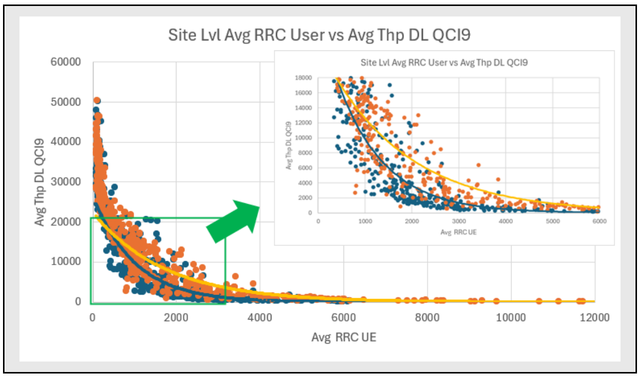

Fig. 4. Scatter plot: Site-level average RRC UE vs. average DL throughput QCI9 (4G) and average NR DL throughput (5G n78). Multi-beam sites (orange) vs. conventional sites (teal). Power-law

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trend curves fitted to each population. Inset: zoomed view of 0–6,000 UE range.

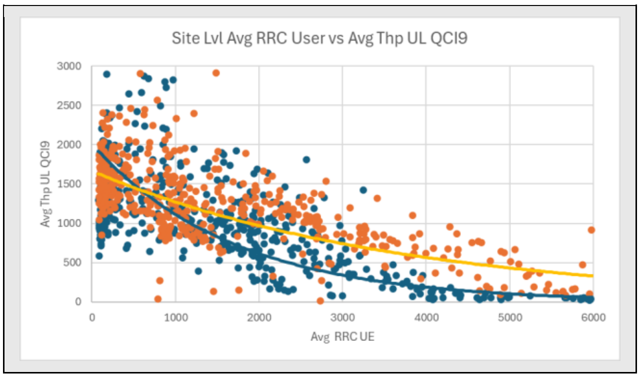

Fig. 5. Scatter plot: Site-level average RRC UE vs. average UL throughput QCI9 (4G) and average NR UL throughput (5G n78). Multi-beam sites (orange) vs. conventional sites (teal).

IX. DISCUSSION AND DESIGN RECOMMENDATIONS

A. Spatial Reuse Is the Primary Mechanism

The consistent gains across all six KPIs and all three technology bands confirm that spatial reuse is the dominant capacity mechanism. The Hexa-Beam configuration's 6× spatial reuse factor explains the magnitude of the user-capacity gains: the network effectively serves users that would have been queued or rejected on a single-cell site. No additional spectrum was required; the existing 4G and 5G allocations were used more efficiently through angular subdivision.

B. Uplink Gains Validate Beam Isolation

The consistently larger percentage gains on the uplink (56.5% for 4G, 67.3% for NR n78, 63.4% for NR n40) compared to the downlink (9.8%, 37.2%, 36.3% respectively) are the clearest indicator that beam isolation is functioning correctly. In conventional cells under heavy load, inter-user uplink interference raises the noise floor for all UEs on the cell, degrading per-user UL SINR. Narrow beams reduce the number of simultaneously transmitting UEs per cell, directly lowering the UL interference floor and enabling the observed throughput improvements.

C. Per-Beam Configuration Is Non-Negotiable

Because each beam is a separate cell, it requires individual RF planning (azimuth, tilt, power), a unique PCI, a separate neighbor list, and independent admission control parameters. Operators must staff for a planning and commissioning workload multiplied by the beam count per band. For a Hexa-Beam site with 5 bands, this means 30 cells to individually commission, compared to 5 for a conventional site. Automated planning tools and parameter consistency checks are strongly recommended to manage this complexity at scale.

D. BBPool Dimensioning Is the Critical Hardware Constraint

The Baseband Processing Pool is the most failure-prone hardware bottleneck in multi-beam deployments. An under-dimensioned BBPool can entirely negate the antenna gains: even with a correctly configured 6-beam antenna, the baseband unit will limit the number of active cells and therefore the number of schedulable users. Pre-dimensioning for the full beam count at peak PRB utilization, with a minimum 20% headroom, must be completed before the event period begins. Post-event analysis should check whether any BBPool hardware ceiling was reached during the peak hour.

E. 5G NR Multi-Beam Amplifies the 4G Gains

The 5G NR n78 band delivered average DL throughput of 54.2 Mbit/s in its inaugural deployment, substantially exceeding the co-located 4G DL throughput of 2.2 Mbit/s, for two reasons: first, the 100 MHz n78 channel provides a much larger PRB pool per beam, so each beam has greater per-user scheduling headroom; second, NR's more efficient air interface — higher-order MCS, flexible numerology, and improved HARQ — translates per-beam spatial reuse into larger absolute throughput. With NR PRB utilization at only 57.4%, substantial additional capacity remains available as 5G device penetration grows. Operators should prioritize 5G NR n78 beam count first in future multi-beam deployments, treating LTE and n40 as coverage and fallback layers.

F. Deployment Strategy for Future Events

Based on the trial evidence, the following deployment strategy is recommended: Hexa Beam for ultra-dense zones where peak site-level concurrent users are expected to exceed 5,000; Dual Beam for high-density zones with peak densities of 1,000–5,000 UE per site; individual per-beam RF planning completed at least four weeks before the event; and BBPool hardware pre-validated against the full 30-cell site load at peak utilization. Per-beam PRB utilization and user count should be monitored throughout the event, with inter-beam load balancing parameters adjusted in real time if any beam approaches 85% PRB utilization.

X. CONCLUSION

This paper reported a live field trial of Dual-Beam and Hexa-Beam multi-beam passive antenna configurations during an ultra-high-density mass-gathering event, covering both 4G LTE (1800 MHz and 2100 MHz) and 5G NR (n78 at 3500 MHz and n40 at 2300 MHz) carriers across five base station sites. A year-on-year comparison framework isolated the antenna configuration change as the primary variable.

On the 4G layer, the multi-beam deployment yielded an 83.7% increase in peak concurrent users served, a 31.4% growth in downlink data volume, a 56.5% uplink throughput improvement, a 13.7% reduction in PRB utilization, and a 7.6% latency reduction — all without additional spectrum. On the 5G NR layer, activated for the first time at these sites, n78 served 12,028 peak concurrent users and 8,474 GB of downlink data at 54.2 Mbit/s average DL throughput, while n40 complemented with 8,019 users and 5,649 GB at 32.6 Mbit/s — together representing 30% of 4G user count and 45% of 4G data volume with substantial PRB headroom for future growth.

Scatter analysis confirmed that the multi-beam advantage is systemic: across all user density levels, multi-beam sites consistently occupied a higher throughput envelope than conventional sites, and served far larger peak user populations. The uplink gains, consistently exceeding downlink gains across all bands, validate beam isolation as the core physical mechanism. Baseband Processing Pool dimensioning was

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identified as the single most critical operational prerequisite for realizing the full multi-beam capacity benefit at scale. Multi-beam antenna technology is strongly recommended as the primary capacity solution for any operator facing ultra-dense event scenarios, mass-gathering connectivity requirements, or peak user densities that exceed the ceiling of conventional sectorization.

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