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Advanced Spectral Efficiency Assessment for Expert 4G/5G RAN Network Design

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Abstract – **In modern 4G and 5G networks, especially in dense urban areas, ensuring reliable coverage at the cell edge remains a major challenge, particularly for indoor users. Operators often apply conservative interference control measures such as aggressive down tilting or avoiding low band deployment, which may reduce intercell interference but can significantly impair user experience in vulnerable locations. This study analyzes an urban cluster in a Central American network where such practices resulted in degraded service quality and low edge throughput. Using spectral efficiency and user experience metrics, underperforming sectors were identified and their root causes classified, with a focus on coverage gaps. Corrective actions including low band activation and tilt optimization yielded substantial SINR and throughput improvements. Compared with the conference version of this work [1], the present study further incorporates a capacity-oriented assessment that distinguishes propagation driven limitations from congestion driven performance degradation and evaluates a set of capacity enhancement mechanisms such as bandwidth expansion, traffic redistribution, densification and advanced high capacity solutions. The results highlight the need for balanced network design that simultaneously addresses coverage and capacity constraints and confirm spectral efficiency analysis as an effective diagnostic foundation for holistic planning in both LTE and NR systems.**

Keywords – **5G/NR, LTE, network performance, spectral efficiency, intercell interference.**

I. Introduction

Mobile networks face growing pressure to deliver consistent service quality across diverse environments, particularly in dense urban areas where coverage and capacity demand often conflict [2–5]. Although 5G evolution prioritizes mid- and high-band spectrum for capacity, low-band frequencies (e.g., 700–800 MHz) remain critical for ensuring robust cell-edge and deep indoor coverage. However, cautious radio planning, characterized by limited low-band deployment and aggressive antenna downtilt, while intended to reduce intercell interference, can significantly impair user experience in vulnerable areas.

This paper investigates these tradeoffs through a study conducted in a live urban cluster of a Central American operator. The analysis is driven by spectral efficiency and user experience metrics, revealing the performance impact of suboptimal frequency-layer strategies. To address these limitations, the study proposes and validates targeted corrective actions, including low-band reactivation and tilt optimization. The core contribution lies in the application of a spectral efficiency–based diagnostic framework and the Band Performance Signature methodology to detect inefficiencies and guide data-driven remediation.

The paper is organized as follows, Section II outlines the theoretical background and discusses the key coverage and capacity tradeoffs in OFDM based systems, while Section III introduces the spectral efficiency framework and the Band Performance Signature methodology. Section IV presents the analysis of the evaluated commercial network together with the identification of radio and capacity related limitations and the assessment of applicable improvement actions. Section V concludes the paper.

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II. Delivering User Experience in 4G/5G: Challenges and Trade-offs

Fourth and fifth generation mobile networks (4G LTE and 5G NR) are based on Orthogonal Frequency Division Multiplexing (OFDM), a significant technological leap compared to the access schemes used in earlier generations—namely TDMA in 2G (GSM) and CDMA/WCDMA in 3G systems. OFDM enables high spectral efficiency, flexible bandwidth utilization, and robust performance in frequency-selective and interference-prone environments. These advancements have fundamentally improved peak data rates, latency, and overall user capacity.

However, despite their architectural superiority, OFDM-based systems introduce new trade-offs. Their performance is highly sensitive to interference, especially in dense deployments, and they rely on precise synchronization and accurate channel estimation. Moreover, coverage at the cell edge and indoors remains a challenge, particularly when higher-frequency spectrum is used. These limitations underline the need for careful radio planning, spectrum layering, and parameter optimization to fully realize the potential of 4G and 5G technologies in real-world deployments.

A. Coverage and Capacity Constraints in 4G/5G Networks

Ensuring consistent and high-quality mobile service in 4G and 5G networks requires addressing a fundamental balance between coverage and capacity. While radio access technologies have significantly evolved, offering improved modulation schemes, advanced scheduling, and multi-band operation, core physical limitations remain. Coverage continues to be constrained by frequency-dependent propagation losses, particularly as deployments shift toward higher bands. These bands offer increased capacity but suffer from limited reach and weak penetration into buildings, often leaving underserved areas at the cell edge and indoors. To suppress interference in dense topologies, operators commonly apply aggressive antenna downtilting or limit low-band reuse. Although such strategies may improve local SINR conditions, they frequently compromise broader coverage and create service blind spots.

On the capacity side, mobile networks are fundamentally limited by the Shannon–Hartley theorem, which defines the maximum achievable data rate of a communication channel as:

$$C = B \cdot \log_2(1 + SINR) \quad (1)$$

$$C = n \cdot B \cdot \log_2(1 + SINR) \quad (2)$$

, where C is channel capacity in bits per second, B is the bandwidth in Hz, and SINR is the signal-to-interference-plus-noise ratio. This relation illustrates that capacity cannot grow indefinitely with bandwidth alone, it is bounded by radio conditions and interference levels. To push beyond this limit, modern systems employ Multiple-Input Multiple-Output (MIMO) techniques, which introduce spatial multiplexing by using multiple transmit and receive antennas. In favorable environments, MIMO effectively creates multiple parallel channels within the same bandwidth, thus increasing capacity beyond the scalar Shannon limit. Particularly in 5G, massive MIMO plays a central role in enhancing spectral efficiency under high-load conditions. Still, the actual gain depends on spatial channel diversity, user distribution, and network geometry.

This makes spectral efficiency defined as the throughput achieved per unit of spectrum a central metric for evaluating network performance. It reflects how effectively limited spectral resources are utilized to deliver consistent service, especially under growing traffic demand. In the sections that follow, we explore spectral efficiency more rigorously, analyzing its behavior across frequency layers and its role in identifying coverage and capacity deficiencies.

B. Spectral efficiency drivers in 4G/5G networks

Spectral efficiency in 4G and 5G networks is primarily driven by link adaptation, which adjusts the modulation and coding scheme (MCS) based on real-time channel conditions reported via the Channel Quality Indicator (CQI). Higher CQI values allow the use of higher-order modulation schemes such as 64-QAM, 256-QAM, increasing the number of bits transmitted per symbol. The CQI-to-modulation and coding scheme mapping can be found in 3GPP TS 36.213, Table 7.2.3-1 and Table 7.2.3-2. In parallel, MIMO techniques enable spatial multiplexing, allowing multiple data streams to be transmitted simultaneously, thereby further enhancing throughput.

In operational networks, spectral efficiency is typically measured as throughput per Physical Resource Block (PRB), reflecting how effectively the available spectrum is utilized under given radio conditions. This metric is directly influenced by user location, interference, scheduler logic, and the richness of the radio environment. As such, spectral efficiency varies across cells and frequency layers, and its analysis is essential for diagnosing both coverage and capacity issues.

C. Evaluation of Spectral Efficiency in 4G/5G systems

Spectral efficiency in mobile networks, both in 4G and 5G, can be assessed through active field measurements or estimated using performance data collected from the RAN system. Active measurements typically involve drive tests, where a UE generates traffic under controlled conditions, and the system logs Key Performance Indicators (KPIs) such as throughput and resource allocation. Spectral efficiency is derived as the ratio between data rate and occupied bandwidth, commonly expressed per PRB. In 5G, this calculation must account for variable PRB sizes due to different numerologies.

Alternatively, data can be obtained directly from network elements via internal traces or probes, offering detailed visibility without requiring physical testing. However, both approaches, drive testing and probing can be resource-intensive and limited in scope.

A more scalable method is to estimate spectral efficiency using standardized performance counters collected across the network. While less granular, this approach offers a broader statistical foundation and avoids the cost and logistical complexity of active measurements. Our proposed methodology builds on this concept and is described in the following section.

III. Band Performance Signature: A Methodology for Spectral Efficiency Assessment

Throughput per PRB is primarily influenced by link adaptation, MIMO performance, and radio interface configuration, particularly the overhead introduced by non-traffic elements in the resource grid. It can be estimated using the formula:

$$Thpt_{per_{PRB}} = (1 - OH) \cdot REperPRB \cdot modul.order \cdot coding\ rate \cdot \#\ MIMO.layers \ldots \quad (3)$$

In Eq. (3), OH represents overhead, i.e., the share of Resource Elements unavailable for user data due to control and reference signalling. The number of REs per PRB is typically 168 in LTE and 84 in 5G. Modulation order and coding rate are functions of link adaptation, while the number of layers depends on MIMO effectiveness.

Spectral efficiency evaluation can be based on RAN performance counters, particularly the CQI distribution collected periodically with high granularity. It is important to account for which CQI mapping table was applied (e.g., up to 64QAM vs. 256QAM), as this affects the coding rate per 3GPP specifications [6]. The number of active MIMO layers and their distribution can be derived from vendor-specific counters, while overhead estimation depends on the configured signal structure and must be considered for accurate results [7].

Number of allocated layers and its distribution in a cell is another important metric to be considered, and can be obtained from different performance counters, depending on RAN vendor. Finally, overhead must be accurately estimated to ensure realistic spectral efficiency calculations. This requires assessment of the radio interface configuration, as various control and reference signals occupy parts of the resource grid, reducing the available capacity for user traffic.

In LTE networks (4G), key contributors to overhead include the Physical Downlink Control Channel (PDCCH), Cell-specific Reference Signals (CRS), Physical Broadcast Channel (PBCH), and Synchronization Signals (PSS/SSS). In 5G NR, the overhead structure differs significantly, with signals such as the Synchronization Signal Block (SSB), Demodulation Reference Signals (DMRS), Channel State Information Reference Signals (CSI-RS – both NZP and ZP), and Tracking Reference Signals (TRS) playing central roles [8].

The accuracy of overhead estimation depends on how many of these signals are considered in the analysis. Configuration analysis may be done based on product information and parameters settings assessment, but in many cases available documentation will not be enough and analysis of Radio interface signalling messages will be needed.

With the spectral efficiency now quantified across different portions of each cell, it becomes possible to directly relate these efficiency profiles to the expected user experience. This mapping requires only two additional elements: the average number of active users in the scheduler and the total amount of available downlink resources expressed in physical resource blocks. By combining these parameters, the spectral efficiency distribution can be translated into realistic throughput estimates, allowing user experience to be inferred with high fidelity for near antenna, moving to median and cell edge conditions. In live LTE and 5G deployments, when a sector fails to meet a defined performance target, which in this study is set to 10 Mbps at the cell edge evaluated at the 90th percentile, the applied analytical methodology reveals that such degradation almost invariably arises from two dominant mechanisms, highlighting one of its key strengths in clearly exposing the underlying cause of insufficient performance.

The first mechanism is related to radio propagation limitations, where insufficient signal strength and adverse propagation conditions lead to a persistent reduction in SINR. These situations commonly occur in deep indoor locations, along obstructed urban canyons, or in scenarios where low band coverage is missing, producing a structural coverage deficit that constrains link adaptation and forces the use of low-order modulation schemes.

The second mechanism is capacity driven and emerges when the sector becomes heavily loaded. As the number of active users increases, the scheduling domain becomes congested, interference grows across neighbouring cells, and the effective SINR distribution deteriorates. The relationship between interference and performance in OFDM systems was already outlined in Section 2, where interference was shown to be the primary limiting factor for both LTE and 5G NR. Consequently, even sectors with adequate nominal coverage may experience substantial throughput degradation under high load, underscoring the importance of distinguishing propagation-driven from capacity-driven inefficiencies when evaluating cell-level spectral performance.

IV. In-Depth Analysis of Live LTE/5G Network Performance

Band Performance Signature (BPS) analysis used for detection anomalies in network performance of commercially deployed 4G/5G for network optimization use cases was demonstrated before [9], and here the outcome of analysis of network performance focused on identification of underperforming areas and improvement of 4G/5G RAN network design is going to be presented in this Section. Before proceeding with the advanced, in-depth analysis, it is important to outline the context of the evaluated network. The study was conducted on the commercial infrastructure of a Tier 1 mobile operator in Central America, within a dense urban environment representative of a city with approximately one million residents. This information ensures that the results reflect the behaviour of a mature, high-capacity network under real-world load conditions. While the analysis centres on LTE, the same analytical framework applies to 5G/NR as covered in previous part of this paper.

The operator holds the following spectrum assets for LTE services:

- L850, 10 MHz in Band B5 (850 MHz)
- AWS, 20 MHz, in Band B66 (1700/2100 MHz)
- AWS-1, 20 MHz in Band B4 (1700/2100 MHz)
- L2600F1 and L2600F2, 30 MHz in Band B7 (2600 MHz), with split as 2x15 MHz

With a total of 80MHz of spectrum available for LTE deployment, the operator benefits from a significant LTE capacity in terms of bandwidth.

A. Band Performance Signature Assessment Findings

The spectral efficiency outcomes derived from the Band Performance Signature (BPS) analysis are shown in Fig 1. The results clearly indicate a frequency-dependent trend, where higher bands exhibit increased spectral efficiency, with B7 leading the performance range and B5 at the bottom, across the percentile distribution.

Best spectral efficiency on layers with highest frequency – 2600 MHz (F1 and F2), with 1.4 Mbps/PRB achieved close to antenna and 0.3 Mbps/PRB at cell edge. AWS performance is coming second (B66 and B4), with 1.2 Mbps/PRB achieved close to antenna and 0.25 Mbps/PRB at cell edge. The worst performing is low band B5 - 850 MHz, with 1 Mbps/PRB achieved close to antenna and 0.2 Mbps/PRB at cell edge.

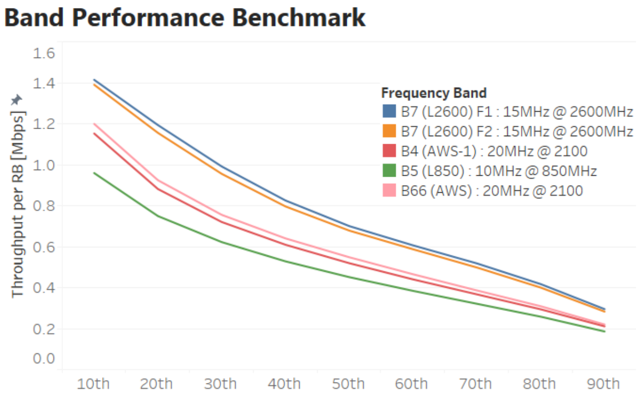

Fig. 1. Band Performance Signature

This pattern has been consistently observed across multiple networks worldwide, based on a comprehensive internal database of BPSs collected under diverse deployment scenarios. The data spans various geographies, propagation environments, and traffic profiles, providing strong empirical grounding for the observed trends.

Lower frequency bands, particularly B5 (850 MHz), are more susceptible to inter-cell interference due to their extended propagation characteristics. While low-band spectrum is essential for coverage, its wide reach often results in greater overlap between neighbouring cells, increasing the likelihood of co-channel interference which degrades SINR conditions, which in turn reduces reported CQI values, forces the use of lower modulation and coding schemes, and ultimately limits the number of bits that can be transmitted per resource block.

As a result, despite offering better coverage, lower bands deliver lower spectral efficiency compared to higher frequency layers. Conversely, higher bands like B7 (2600 MHz) benefit from reduced interference zones, allowing for more consistent high-throughput operation even under loaded conditions.

B. Multi-Operator Comparative Analysis of Spectral Efficiency Across Frequency Layers

This analysis emerged from the operator's need to identify coverage deficiencies and define actionable strategies for their resolution. As previously discussed, the assessment leverages a comprehensive database of BPS collected across numerous global networks, enabling robust comparative insights, shown in Fig. 2. and 3.

In this specific case, cross-operator benchmarking reveals an atypical trend: the high-band layer is among the weakest in terms of spectral efficiency, while the low-band layer demonstrates relatively strong performance. This unexpected situation strongly suggests the lack of L850 carrier deployment, underscoring the need for immediate attention to low-band layer expansion and configuration. Sector-level configuration analysis confirms this, showing that approximately 40% of sectors are missing low-band deployment.

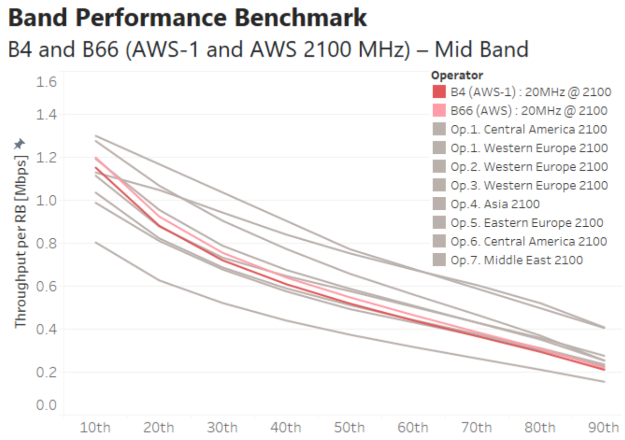

Fig. 2. Band Performance Signature - Mid band benchmark

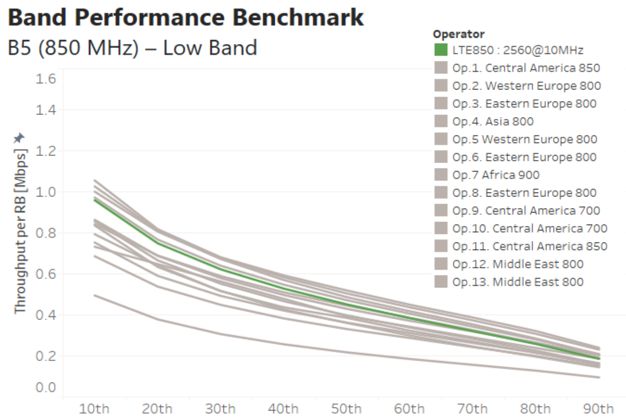

Fig. 3 Band Performance Signature - Low band benchmark

C. Band Performance Signature assessment findings

As outlined in Section 3, reduced spectral efficiency in operational networks arises primarily from radio related limitations or from capacity driven constraints. Recognizing this distinction is essential for correct interpretation of performance degradation. A key strength of the Band Performance Signature methodology is its ability to clearly separate these two mechanisms by providing a rigorous, data-based characterization of layer behaviour. The results of the analysis performed in this study confirm this capability, showing that approximately 68% of all evaluated sectors operate with satisfactory spectral efficiency thus user experience, while the remaining underperforming group is divided between radio related issues, which account for about 8%, and capacity driven limitations, which represent roughly 23% of total sector amount in given test cluster. This diagnostic resolution makes it possible to determine whether the degradation originates from propagation effects or from congestion driven interference, which in turn ensures that corrective actions are aligned with the true nature of the problem.

D. Radio-Related Efficiency Limitations

The analysis of underperforming sectors revealed a set of recurring patterns linked to insufficient coverage and inefficient spectrum utilization. As previously outlined, a significant number of underperforming sectors in the analyzed cluster were identified as lacking low-band deployment. Low band introduction is going to result in substantial improvements in coverage, indoor penetration, and SINR distribution, especially on cell edge (Fig. 4), for sectors where it was not deployed before. Figure 4 illustrates the changes in best-server SINR following the addition of the low-band layer on the designated sites. Simulations were conducted in Atoll RF planning tool.

Fig. 4. SINR Improvements with introduction of low band frequency

For sectors where low band is already deployed, RF design optimization actions can focus on adjusting tilt, azimuth, or power settings, and traffic redistribution, which again can be accurately modelled in radio planning tools such as Atoll. In this case the main action that was considered was the reduction of the antenna tilt. Example of simulations based on current traffic distribution and signal strength data used to pre-validate the impact of proposed antenna tilt changes before implementation is presented on Fig. 5, which refers to different sectors, another part of the cluster not related to Fig. 4.

Fig. 5. SINR Improvements with RF re-design and antenna tilt

In scenarios with budget or hardware constraints, low band hardware reshuffling represents a feasible option when applied to sectors whose performance remains stable even after the removal of the low band layer. Since low band spectrum provides the broadest propagation footprint, its extraction must be limited to dense urban areas where LTE coverage is already strong and where the footprint is preserved by higher band layers. Before any reallocation is performed, the donor sector must be assessed for long term traffic growth and validated through RF planning simulations to ensure that neither coverage nor mobility performance will be degraded. Once technically confirmed, the released low band hardware can be reassigned to suburban or rural sectors where coverage limitations are more pronounced and where the additional low band layer provides the highest benefit. The comparison presented in Fig. 6 illustrates this principle by evaluating cell edge throughput under double the traffic (100 percent traffic growth) [10] with and without the low band layer, thereby determining which sectors can safely act as donors and which require the low band layer to maintain acceptable performance.

In the analyzed cluster, applying low-band deployment, RF optimization, and antenna uptilting led to resolution or significant improvement in about 60% of previously radio related underperforming sectors.

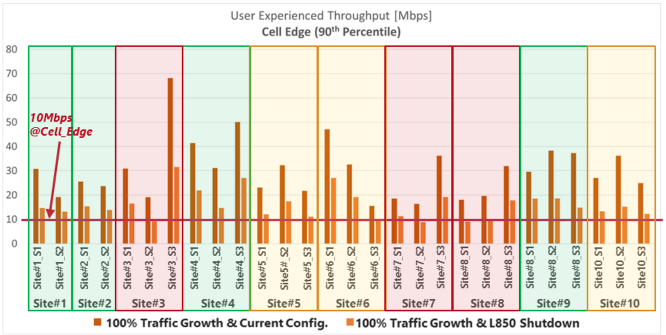

Fig. 6. Cell-edge throughput under traffic growth with and without low band

E. Capacity Related Efficiency Limitations

Only a decade ago, capacity shortages were most addressed through the construction of new sites, since the available spectrum and technological options on a given location were very limited. Today, however, operators benefit from a fundamentally different spectrum and technology landscape, making capacity enhancement significantly more flexible and less infrastructure intensive.

This shift is primarily driven by the coexistence of multiple radio access technologies on the same grid, together with the availability of a broader set of frequency bands within each technology. The expansion of operator spectrum holdings results from regulatory auctions of new bands, as well as from large-scale refarming initiatives that have gradually reduced the footprint of legacy systems such as GSM and UMTS. Spectrum that was once reserved for these earlier generations is increasingly being reassigned to LTE and 5G, where it can be used far more efficiently both in terms of spectral utilization and overall user throughput.

The combined effect of these developments is that capacity limitations, while still a significant source of efficiency loss, can now be mitigated through a wide portfolio of actions that remain within the boundaries of an existing site. Additional carriers across different layers, improved spectrum contiguity, redistribution of traffic toward newer technologies, and more efficient use of available mid- and high-band assets all contribute to reducing the likelihood that a sector becomes congested. As a result, the relationship between load, interference, and spectral efficiency, although still central to performance analysis, operates in an environment with considerably more tools available for practical capacity relief than in the past.

After identifying a sector as underperforming due to excessive load, the first step is to assess whether additional LTE bandwidth can be introduced on that site. This represents the simplest and least intrusive capacity enhancement option, particularly because the operator requested that the analysis focus on LTE rather than multi-technology strategies. In the examined cluster, only a smaller portion of capacity-limited sectors still have unused LTE spectrum and can benefit from straightforward bandwidth expansion.

The majority, however, already operate with the full 80MHz allocation, leaving no remaining spectrum for intra-LTE expansion and therefore requiring alternative capacity solutions. One approach is the redistribution of traffic toward neighbouring sectors that remain underutilized. By adjusting cell reselection biases, handover thresholds, and RF design parameters, it is possible to redirect part of the load to adjacent cells, thereby reducing scheduler congestion on the affected sector.

When the surrounding topology lacks sufficient capacity headroom for redistribution, network densification becomes the next viable option. Introducing new sites at carefully selected locations shortens the average cell radius, reduces the number of users served per sector, and improves the SINR environment, providing sustainable long-term relief. In practice, the identification and prioritization of new site candidates relies on analysing scheduler load patterns, particularly the number of active users during the busy hour, and locating geographical zones where multiple congested sectors overlap. This approach was proven in practice to show good resutls and improve Return on Investments – RoI. The map presented in Fig. 7 illustrates this principle, highlighting the areas where offered traffic per busy hour reaches the highest values and where existing LTE sectors are unable to absorb the demand. Once new sites are deployed, a comprehensive RF re-design is required to ensure proper load distribution, minimize intercell interference, and preserve mobility performance across the newly formed topology, and finally to maximize the beneftis of new assets.

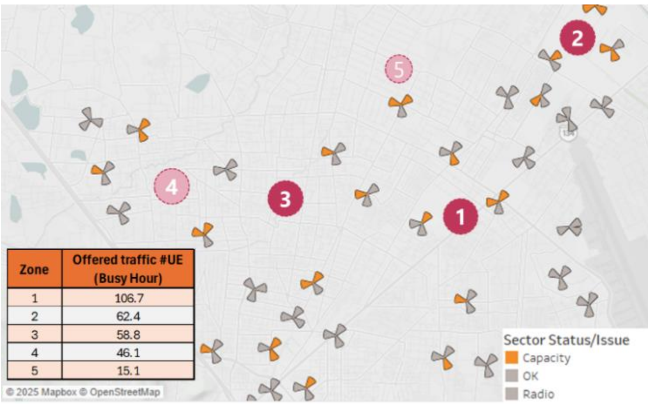

Fig. 7. SINR Improvements achieved with RF re-design and antenna tilt

Another important mechanism is inter-technology offloading, particularly from LTE toward 5G. With NR layers increasingly available, with higher typically bandwidth comparing LTE and improved spectral efficiency [11], shifting suitable traffic classes to 5G reduces LTE scheduler load while simultaneously improving user throughput on both technologies.

Finally, advanced capacity solutions can be applied when spectrum is scarce and densification is constrained. One option is additions of new sectors, and deployments of more than typically implemented three sectors per site. However, this technique potentially introduces drawback of irregular grid, and RF redesign might be needed to minimize potential problems with interference. Another option is introduction of massive MIMO solutions and cell splitting, where additional spatially separated resource grids are created through beamforming. Both techniques aim to increase the effective resource pool available to users, although their achievable gains depend strongly on interference management and the spatial distribution of the traffic load. Each of these strategies provide a comprehensive set of tools for alleviating congestion in sectors where spectral expansion is no longer possible.

One example of segmentation of sites with insufficient capacity segmentation on deployed bandwidth criteria, and overview of actions is presented on Fig.8.

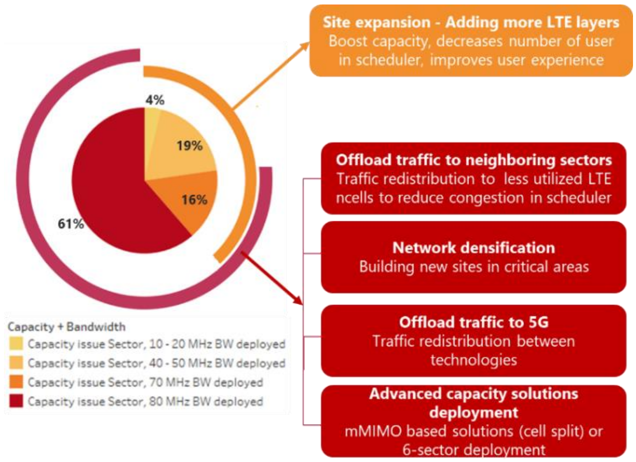

Fig. 8. Sites with insufficient capacity – overview of actions

V. Conclusion

In this paper, the potential benefits of advanced spectral efficiency analytics in the 4G and 5G RAN design process were evaluated. The fundamental challenge remains the need to balance intercell interference control with the provision of sufficient signal strength across diverse propagation environments. The introduced Band Performance Signature methodology has proven particularly effective in distinguishing whether performance degradation originates from radio related limitations or from capacity driven constraints, allowing for a targeted and technically consistent remediation strategy. Results obtained in the analyzed network of mobile operator in Central America, showed that radio related issues represented only a portion of the overall underperforming sectors, and for this subset, more than sixty percent could be improved through low-band deployment, configuration uplift, RF design optimization, and antenna tilt adjustments. Capacity driven limitations, on the other hand, require a different set of actions, including traffic redistribution, leveraging 4G offload, densification, or advanced capacity solutions. These findings confirm that the proposed methodology enables a holistic and data driven approach to coverage, quality, and capacity planning, supports efficient utilization of spectrum and hardware assets, and is fully applicable to both LTE and 5G networks.

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