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Strategies for 4G/5G Coexistence in High-Density Urban Clusters (India)

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Abstract: ***This article presents a systematic analysis of strategies for the coexistence of fourth- and fifth-generation networks in high-density urban clusters, where a high concentration of subscribers, devices, and services under limited radio-frequency resources leads to interference-limited network operation. The study is conducted as an analytical synthesis of peer-reviewed scientific publications and focuses on comparing spectral, architectural, mobility-related, and infrastructure-level coexistence mechanisms without quantitative aggregation of results due to methodological heterogeneity of the sources. Particular attention is paid to the role of the FR1 band as the primary zone of overlap between LTE and 5G in non-standalone architectures, as well as to the impact of full frequency reuse on the nature of interference interactions in dense urban environments. It is shown that the dominant constraint on capacity scaling in such scenarios is interference rather than nominal spectrum scarcity, which shifts the emphasis from static planning to dynamic radio resource allocation and intelligent control mechanisms. It is established that the highest robustness is demonstrated by architectures in which dynamic spectrum sharing and algorithmic decision-support mechanisms are integrated with non-standalone deployment schemes, mobility management loops, and infrastructure-sharing mechanisms. The analysis shows that the effectiveness of 4G/5G coexistence is determined not by the isolated application of individual technologies, but by the degree of their coordination within a managed operational control loop. The article will be of interest to mobile network researchers, radio network architects, cellular optimization engineers, and specialists involved in the planning and operation of urban communication networks.***

Keywords: 4G, 5G, network coexistence, high-density urban environments, infrastructure sharing

1. Introduction

The joint operation of fourth- and fifth-generation networks in dense urban environments is becoming one of the key scientific and practical tasks of modern mobile communications. The growth in the density of subscribers, services, and connected devices, given limited radio-frequency resources, leads to urban networks operating in an interference-limited regime, where frequency reuse and mutual interference between cells and radio technologies become the main cause of degradation in quality of service (QoS) and quality of experience (QoE) indicators [7]. Under these conditions, 4G and 5G coexistence strategies acquire systemic importance for radio network stability and the preservation of the required level of communication quality.

The problem is particularly relevant for India, where the early deployment of fifth-generation networks in mass scenarios relies on existing LTE infrastructure and requires the use of network interworking architectures, primarily non-standalone (NSA), in shared FR1 frequency bands [3]. Such a model ensures continuity of coverage and mobility but simultaneously intensifies inter-cell and inter-technology interference in dense urban clusters. In response to this, modern research observes a transition from static radio resource allocation mechanisms to dynamic spectrum sharing strategies, including Dynamic Spectrum Sharing and Dynamic Spectrum Access, supplemented by intelligent resource planning [2]. The practical applicability of these approaches is confirmed by industrial experience in optimizing multi-layer NSA networks in dense urban zones of India, particularly in the Gujarat region, forming an applied context for evaluating the proposed strategies.

Within one such industrial project in the Gujarat region, a large-scale LTE macro network design and expansion program was implemented, covering over 100 new base stations and oriented toward increasing territorial coverage and network capacity under high subscriber density conditions. As a result of the deployment, a network coverage increase of approximately 20% was achieved, with architectural decisions regarding radio part placement and configuration laid down taking into account subsequent network evolution to fifth-generation non-standalone architectures and joint LTE and NR operation.

The aim of the study is the systematization and analytical assessment of 4G and 5G network coexistence strategies in dense urban clusters of India, forming an integrated portfolio of solutions at the spectrum, radio access, mobility, and infrastructure levels. To achieve this goal, the work addresses the following tasks:

- Identify key sources of QoS/QoE degradation during joint LTE and 5G operation in dense urban environments;
- Systematize methods of dynamic spectrum and interference management based on DSS/DSA and intelligent algorithms;
- Analyze architectural and infrastructural solutions ensuring mobility stability and operational efficiency of urban networks.

The research hypothesis is that sustainable coexistence of fourth- and fifth-generation networks in dense urban clusters is achieved through the coordinated management of interference, spectrum, mobility, and infrastructure within a single managed loop.

The scientific novelty of the work lies in forming a holistic approach to 4G and 5G coexistence, in which spectral, architectural, mobility, and infrastructural solutions are viewed not in isolation, but as interconnected elements of a single managed loop adapted to the conditions of high-density urban clusters in India.

2. Materials and Methods

Research materials include scientific publications from 2022-2025 dedicated to 4G and 5G network coexistence strategies in high-density urban environments. As a methodological basis for classifying interference mechanisms, the approach proposed in the review study by Alzubaidi et al. [1] is used, in which interference management and suppression strategies are systematized by principle of action. Within the present work, these mechanisms are grouped into temporal, frequency, spatial, and orchestration loops in accordance with this classification.

Dynamic spectrum sharing and dynamic spectrum access approaches are applied to analyze the spectral level of coexistence. The methodological base for this analysis is the review by Gbenga-Ilori et al. [2], which describes DSS and DSA mechanisms for joint LTE and NR operation. In the study, these approaches serve as a basis for assessing adaptive spectral resource reallocation under high user density conditions. Architectural network coexistence methods are analyzed based on non-standalone deployment schemes, dual connectivity, and carrier aggregation. The approach presented in the work of Imam-Fulani et al. [3], where the FR1 band is viewed as the main LTE and 5G NR overlap zone, is used as the initial architectural model. In the present study, these architectural solutions are applied to analyze inter-technology interaction in dense urban clusters.

The methodology for comparative assessment of coexistence strategies is based on the use of standard radio connection quality and interference indicators. A set of metrics, including interference-to-noise ratio, signal-to-interference-plus-noise ratio, bit error probability, throughput, latency, spectral efficiency, and packet success rate, is borrowed from the work of Parveen et al. [7]. These indicators are used in the study to compare the effectiveness of various spectrum and interference management mechanisms.

Indicators of handover frequency and radio link failures are applied to analyze mobility stability in ultra-dense heterogeneous networks. The methodological basis for assessing the impact of handover control parameters, including handover threshold and time-to-trigger, is borrowed from the review by Saoud et al. [9]. In the present work, these data are used to assess the impact of coexistence strategies on connection stability and quality of service.

The economic component of the methodology is based on analyzing the efficiency of infrastructure sharing when deploying networks in dense urban environments. The study by Sümer et al. [10] is used as a source of quantitative indicators for capital and operational expenditure reduction. Within this work, economic efficiency indicators are applied to assess the feasibility of 4G and 5G coexistence strategies from the perspective of operational costs and network scalability.

3. Results

Within the framework of this study, results are understood as analytically established patterns and structural effects identified based on a comparative analysis of published scientific and industrial sources. The presented conclusions are not results of empirical measurements but reflect generalized effects of applying various LTE and 5G network coexistence strategies in dense urban environments. In the process of analyzing 4G and 5G network coexistence in dense urban clusters, it was established that massive IoT services form an independent load class that fundamentally does not align with classical cellular radio access architecture [6]. High device density, low throughput requirements, and the asynchronous nature of traffic lead to radio resource overuse and increased interference impact in the RAN, exacerbating quality of service degradation under frequency reuse conditions [1]. Within this study, this problem is viewed as structural, rather than a consequence of insufficient network parameter optimization. Table 1 examines the main characteristics of LPWAN technologies.

Table 1: Comparison of LPWAN technologies by frequency range, throughput, and channel bandwidth (Compiled by the author based on source: [6])

Technology	Frequency range	Latency	Throughput	Range (km)	Channel bandwidth
LoRaWAN	< 1 GHz	Low	≤ 40 kbps	30	≤ 500 kHz
Sigfox	< 1 GHz	Low	≤ 150 bps	50	100 kHz
Dash	< 1 GHz	Low	≤ 200 kbps	10	≤ 200 kHz
RPMA	2.4 GHz	Low	≤ 19,000 bps	20	80 MHz
Weightless-W	TVWS (≤ 900 MHz)	Low	≤ 10 Mbps	20	5 MHz
Weightless-N	< 1 GHz	Low	≤ 100 bps	5	200 Hz
Weightless-P	880–915 MHz	Low	≤ 100 kbps	4	≤ 100 kHz
LTE-M	455–2600 MHz	Very low	≤ 1 Mbps	5	1.44–5 MHz
5G eMTC	455–3500 MHz	Very low	≤ 2 Mbps	7	1.44–5 MHz
NB-IoT	455–2100 MHz	Very low	≤ 0.54 Mbps	7	180–200 kHz
5G NB2-IoT	455–3500 MHz	Very low	≤ 0.78 Mbps	10	≤ 500 kHz
LTE Cat1	455–3500 MHz	Very low	≤ 10 Mbps	5	20 MHz
EC-GSM-IoT	395–1060 MHz	Very low	≤ 0.5 Mbps	8	≤ 500 kHz
IEEE 802.11ah	< 1 GHz	Very low	≤ 30 Mbps	2	≤ 16 MHz

Analytical comparison of parameters presented in Table 1 shows that LPWAN technologies form a separate operational layer optimized for long-range communication and minimal spectrum usage, which fundamentally reduces their contribution to cellular network interference load [6]. Within the present study, this layer is viewed not as an auxiliary means of expanding the service zone, but as an active mechanism for structural radio access network offloading in dense urban environments.

Transferring a significant share of massive IoT traffic to LPWAN access allows reducing competition for radio resources in the FR1 band, where joint LTE and 5G operation in non-standalone architectures is implemented [3]. This functional traffic separation changes the nature of interference interaction between cells, as it frees RAN resources for services with high throughput and latency requirements [4]. In the context of radio frequency spectrum sharing, this is viewed as an indirect but systemic factor increasing the stability of network coexistence architectures.

From the perspective of this study, the heterogeneous connectivity model using LPWAN forms the "long arm" of the urban network, extending the service radius for mass devices without a proportional increase in interference and without increasing base station density. This configuration is considered a mandatory element of 4G and 5G coexistence strategies in dense urban clusters oriented toward radio network scalability and stability.

In the process of analyzing 4G and 5G network coexistence strategies in dense urban environments, it was established that economic deployment constraints become comparable in significance to radio-technical interference and throughput factors [10]. High base station density, limited available sites, and growth in capital and operational expenditures form structural pressure on capacity and coverage scaling, requiring the application of infrastructure sharing mechanisms as an element of network coexistence architecture. Within the present study, such mechanisms are viewed not as an auxiliary cost-reduction measure, but as an active factor influencing the stability and reproducibility of network deployment in dense urban environments. Figure 1 presents the distribution of the economic effect of various forms of infrastructure sharing, demonstrating the scale of cost reduction when transitioning from passive to deeper levels of joint deployment.

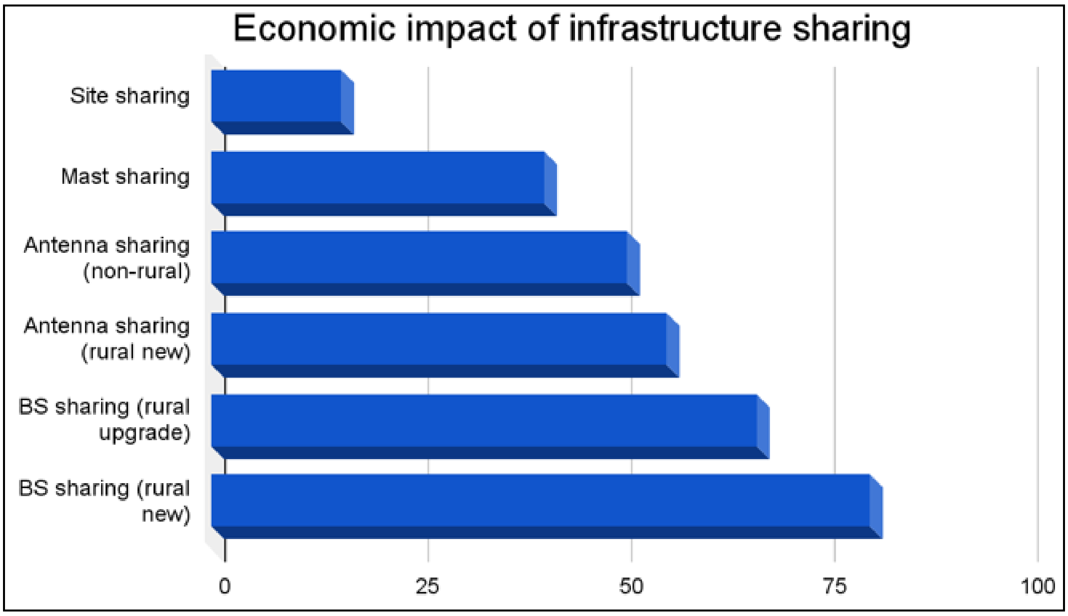

Figure 1: Economic effect of infrastructure sharing (compiled by the author based on source: [10])

Analysis of data presented in the diagram shows sequential strengthening of the economic effect as the level of infrastructure sharing deepens. Site sharing provides cost reduction at the level of 16%, reflecting the effect of splitting rental and basic operational expenses without interfering with the network radio part. Transitioning to mast sharing increases the effect to 41%, as capital expenditures on constructing supporting structures and associated engineering works are additionally reduced. Antenna sharing in non-urban environments demonstrates a 51% effect, indicating substantial savings due to unifying passive radio-frequency components and reducing the number of antenna systems. For new deployments in rural and peripheral zones, antenna sharing provides up to 56% cost reduction, associated with eliminating duplicate infrastructure design and installation stages. Base station sharing when modernizing existing networks leads to a 67% cost reduction, reflecting the effect of reusing the power, transport, and hardware base during radio technology upgrades. The maximum value, reaching 81%, is observed with base station sharing in new deployments, where parallel infrastructure construction by multiple operators is eliminated and the greatest economy of scale at the capital stage is achieved.

From an architectural point of view, infrastructure sharing is viewed as an element supporting the deployment of fifth-generation non-standalone architectures, in which fourth- and fifth-generation networks function jointly in shared frequency bands [4]. Reducing costs for basic infrastructure allows reallocating resources in favor of intelligent radio network management mechanisms, including dynamic radio frequency spectrum allocation and adaptive planning, which strengthens the systemic stability of deployment scenarios in dense urban environments. Simultaneously, this creates conditions for more flexible management of mobility and cell density without increasing the probability of failures and overloads.

Thus, within the conducted analysis, infrastructure sharing is interpreted as an economically measurable and structurally significant element of 4G and 5G network coexistence strategies in dense urban environments, exerting a direct influence on deployment reproducibility, capacity scaling, and the stability of network coexistence architectures.

4. Discussion

In the process of interpreting the obtained results, LTE and NR coexistence in dense urban environments is viewed not as a local spectrum optimization task, but as a managed loop in which dynamic radio frequency resource allocation and algorithmic decision-making mechanisms form the basis of network coexistence stability. Under conditions of full frequency reuse FR=1, it is interference, not physical spectrum scarcity, that becomes the dominant constraint on capacity scaling, fundamentally shifting emphasis from static planning schemes to adaptive and predictive management mechanisms [2]. Within the present study, DSS and DSA are treated as the functional core of such a loop, ensuring coordinated LTE and NR operation in shared frequency bands without disrupting existing services. Table 2 examines how various DSA approaches and artificial intelligence methods are applied to manage joint LTE and 5G operation under conditions of spectrum deficit and high interference load.

Table 2: AI/DSA strategies for 4G/5G coexistence in a dense urban environment
(Compiled by the author based on source: [2])

AI/DSA strategy	Mechanism	Role in dense-urban 4G/5G coexistence	Reported effect
Dynamic Spectrum Sharing (3GPP)	Joint LTE/NR carrier usage	Smooth 4G→5G migration without LTE shutdown	Reduced spectrum scarcity
ML-based traffic prediction	Demand and load forecasting	Proactive LTE/NR resource allocation	Improved QoS at peak load
RL-based DSA	Learning spectrum access policy	Interference reduction in dense deployments	Higher network stability
Cooperative CNN sensing	Collaborative channel detection	Improved coexistence in HetNet	90.68% accuracy
ResNet-based sensing	Deep residual learning	Robust detection at low SNR	94.5% accuracy
LSTM + SCF sensing	Temporal correlation modeling	Stable DSA in dynamic environments	99.8% accuracy
GenAI demand shaping	Traffic compression and scheduling	Load and interference reduction	Network energy savings

Analysis of the presented strategies shows that DSS and DSA in dense urban environments cannot be viewed as self-sufficient mechanisms. With FR=1, their practical applicability directly depends on integration with inter-cell coordination, power control, and spatial separation methods, since without these components, dynamic spectrum reallocation merely redistributes interference in time but does not reduce its level. Within this study, artificial intelligence is viewed as a connecting link between spectral and radio network levels, ensuring the transition from reactive control schemes to proactive and distributed decision-making.

Significantly, AI-driven spectral sensing and planning mechanisms change the very logic of coexistence management. The network ceases to react to already arisen congestion and begins to adapt to expected traffic and radio environment changes. This allows viewing DSS/DSA not as a temporary solution for the 4G to 5G migration period, but as a stable architectural element of joint LTE and NR operation in dense urban clusters. In this context, artificial intelligence acts not as an add-on to existing mechanisms, but as the basis of a managed loop for sustainable network coexistence.

In dense urban environments, fourth- and fifth-generation network coexistence strategies form a reproducible system of architectural and operational solutions oriented toward the specifics of Indian urban deployment scenarios. The main feature of such scenarios is the evolutionary nature of 5G implementation, where fifth-generation networks are overlaid on existing large-scale LTE infrastructure. The architectural basis of this process is formed through non-standalone architectures, dual connectivity, and carrier aggregation in the FR1 band as the main LTE and NR overlap zone [3]. The applicability of this architectural logic is confirmed by the practice of optimizing multi-layer fifth-generation non-standalone networks in dense urban environments, where joint 2G, 4G, and 5G operation is implemented within a single radio network loop. During the optimization of such configurations, a network latency reduction of approximately 30% was recorded due to correct anchor LTE cell tuning and load distribution between layers, alongside a peak network throughput increase of around 35% during busy hours. These results were achieved without increasing base station density and while maintaining mobility stability under high handover frequency conditions. In this logic, coexistence is treated not as a temporary state, but as a stable phase of radio network development requiring systemic management at the architectural level.

A substantial element of such a coordinated system is the mobility management loop. In ultra-dense heterogeneous networks, reducing cell radii and increasing the number of radio access levels leads to a sharp increase in the number of handovers and an increased risk of radio link failures. Within the discussion, mobility results are interpreted as an indication of the necessity to transition from static handover parameter tuning to adaptive and predictive control schemes. The increased sensitivity of connection quality indicators to handover threshold and time-to-trigger parameters makes the mobility loop a critical element of LTE and 5G coexistence stability in a dense urban environment [9]. Simultaneously, mobility is viewed not in isolation but in interconnection with interference and load distribution between network layers. An additional factor increasing the manageability of such configurations is the automation of individual radio network planning and optimization stages. Using software tools for automated frequency planning parameter tuning and interference analysis allowed reducing the volume of manual engineering operations by approximately 50%, simultaneously increasing decision reproducibility. In the context of dense urban environments, this approach is viewed as a means of reducing operational risks during network scaling, rather than as isolated optimization of individual parameters.

The industrial context associated with macro network expansion projects and the optimization of non-standalone multi-layer configurations in Indian regions is used in this study as a practical validation of the applicability of the proposed "playbook." Experience in large-scale macro cell design and subsequent optimization of high-tech networks shows that the coordinated application of architectural, spectral, and algorithmic mechanisms allows managing interference growth and load without losing network stability [11]. Importantly, this context confirms the reproducibility of coexistence strategies in theoretical models and real conditions of dense construction and high subscriber concentration.

Thus, the discussion consolidates separate coexistence loops-architectural, mobility, and operational—into a unified applied "playbook" oriented toward Indian deployment conditions, where LTE and NR coexistence stability is determined by solution consistency rather than individual technology efficiency.

5. Conclusion

The conducted study shows that 4G and 5G network coexistence in dense urban clusters should be conceptualized not as a collection of independent technological measures, but as a coordinated system of managed loops. Joint operation stability is formed through the integration of interference management mechanisms, intelligent radio frequency spectrum allocation, non-standalone deployment architectures in the FR1 band, adaptive mobility management, and infrastructure sharing mechanisms.

It is shown that in dense urban environments, the economic feasibility of capacity and coverage growth becomes an equal factor alongside radio-technical constraints. Infrastructure sharing in this work is treated as a systemic mechanism allowing costs to be kept under control while maintaining network architectural flexibility. This creates the opportunity to direct freed resources toward intelligent radio network management mechanisms critical for operation in an interference-limited regime.

For Indian deployment scenarios, the article establishes a practical linkage wherein fifth-generation network implementation over a large-scale LTE base is realized through joint operation in the FR1 band, dynamic spectrum management, and a dedicated mobility management loop. This configuration allows viewing LTE and 5G coexistence not as a temporary transition stage, but as a stable phase of urban radio network development. It is the consistency of architectural, spectral, and operational solutions that determines the possibility of long-term network scaling under conditions of high subscriber and service density.

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