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STRATEGIC UMTS SUNSET IMPLEMENTATION IN NATIONAL-SCALE MOBILE NETWORKS: METHODOLOGY, RISKS, AND PERFORMANCE GAINS

Summary. *The progressive retirement of legacy cellular technologies represents one of the most intricate operational challenges faced by contemporary mobile network operators. While the migration toward LTE and fifth-generation infrastructures has been widely documented, the methodological foundations governing the controlled sunset of earlier radio access technologies remain comparatively underexplored. In particular, the decommissioning of UMTS networks introduces a complex interplay between spectrum refarming, traffic redistribution, service continuity, and operational risk. If performed without analytical guidance, the shutdown of legacy radio layers may provoke severe congestion phenomena, localized capacity collapse, and degradation of user-perceived service quality.*

This study proposes a structured analytical framework for strategic UMTS sunset implementation within national-scale mobile networks. The research develops a mathematical model that conceptualizes technology retirement not as an isolated operational procedure but as a multi-stage optimization problem embedded within the broader dynamics of traffic migration and spectrum reallocation. The model integrates probabilistic risk estimation, predictive traffic

forecasting, and performance-oriented optimization in order to determine the most balanced trajectory of legacy infrastructure decommissioning.

To validate the analytical model, a dedicated experimental software environment was implemented in Python, enabling simulation of progressive UMTS shutdown scenarios and comparative evaluation of alternative decision strategies. The system incorporates modules for dataset preprocessing, predictive traffic modeling, iterative sunset simulation, and analytical visualization of network behavior. An openly available dataset describing cellular network performance indicators was used to construct a synthetic yet statistically plausible representation of sector-level radio conditions.

Simulation results demonstrate that risk-aware sunset strategies significantly reduce the probability of network overload events while preserving higher LTE throughput levels during the transition process. In contrast, load-driven or stochastic shutdown strategies exhibit increased susceptibility to blackout conditions under heavy traffic migration scenarios. The obtained findings indicate that integrating predictive modeling and probabilistic risk assessment into sunset planning procedures enables a more stable and resource-efficient transformation of cellular infrastructures.

The proposed methodological framework contributes to the emerging body of research on technological transitions in mobile networks by providing a coherent analytical approach to legacy technology retirement. Beyond its theoretical implications, the model may serve as a practical decision-support instrument for mobile operators planning large-scale spectrum refarming and infrastructure modernization initiatives.

Key words: *UMTS sunset, cellular network evolution, spectrum refarming, traffic migration modeling, LTE capacity management, risk-aware optimization, radio access network planning, network resilience.*

Introduction. The architecture of contemporary cellular infrastructures is undergoing a profound technological realignment as legacy second- and third-generation systems gradually yield their functional role to LTE and emerging fifth-generation platforms. This transition has markedly expanded spectral efficiency, transmission capacity, and responsiveness of wireless communication environments. Yet the evolutionary replacement of radio technologies inevitably entails the retirement of earlier standards whose operational relevance is steadily diminishing. Among them, the Universal Mobile Telecommunications System (UMTS) represents one of the most delicate elements of the transition process. Despite its declining strategic significance, UMTS still processes a residual portion of network traffic and frequently functions as a fallback coverage layer. Consequently, an abrupt or poorly orchestrated shutdown may trigger localized congestion within LTE infrastructure, disrupt service continuity, and compromise connectivity for devices that remain partially dependent on legacy standards.

For this reason, the sunset of UMTS cannot be interpreted merely as a routine act of spectrum refarming. In operational reality it constitutes a complex infrastructural metamorphosis involving traffic migration, redistribution of radio resources, and careful containment of stability risks across the cellular ecosystem. Mobile network operators therefore confront a twofold strategic dilemma: determining not only the appropriate moment for withdrawing legacy infrastructure but also the trajectory of this transition so that service degradation remains practically imperceptible. Although existing research extensively addresses spectrum efficiency, radio resource management, and architectural evolution of cellular systems, the methodological formalization of large-scale technology retirement remains strikingly fragmented. In many practical cases, operational decisions rely more on engineering intuition than on analytical frameworks capable of anticipating traffic redistribution and capacity imbalances. To bridge this gap, the present study develops a structured analytical framework that models the progressive withdrawal of UMTS infrastructure while evaluating

its implications for LTE performance through a synthesis of mathematical modeling, predictive traffic estimation, and computational simulation.

Recent research analysis. The body of contemporary research devoted to the transformation of cellular infrastructures, spectrum refarming, and traffic redistribution reveals a substantial accumulation of studies focused on architectural evolution, radio resource optimization, and resilience of mobile systems. Nevertheless, despite this rather extensive scholarly landscape, the literature almost never articulates a coherent methodological paradigm for the strategic retirement of UMTS technology at the national level. Most publications concentrate either on macro-level architectural transformations or on isolated mechanisms of performance optimization, leaving the systematic linkage between legacy technology phase-out, service degradation risks, staged migration procedures, and measurable performance benefits only sporadically addressed.

Dwivedi and colleagues investigate long-term architectural shifts in mobile communication systems, tracing the transition from early cellular generations toward contemporary 5G infrastructures [12]. Their comparative analysis encompasses paradigms such as software-defined networking, network function virtualization, mobile edge computing, network slicing, and functional disaggregation of radio and core network elements. The authors identify key performance targets for next-generation networks, including higher traffic capacity, reduced latency, and greater architectural flexibility. Within this context, the decommissioning of obsolete radio layers is implicitly interpreted as a natural element of broader architectural reconfiguration. However, the study does not translate these principles into a structured operational methodology for retiring a specific technology within a nationwide network, which largely stems from the survey-oriented nature of the work and its emphasis on emerging 5G paradigms.

Asplund and co-authors examine cellular capacity fundamentals through theoretical modeling of spectrum utilization, spectral efficiency, and network densification [2]. Their conceptual result suggests that throughput improvements

can emerge only from expansion of spectrum resources, enhancement of spectral efficiency, or infrastructure densification. This reasoning clarifies why reallocating frequencies previously occupied by legacy systems frequently leads to substantial improvements in LTE capacity. Yet the study remains silent on the operational boundaries of safe spectrum withdrawal, user migration dynamics, and criteria determining the appropriate moment for technology retirement.

Sahin and collaborators explore mobile network evolution from the perspective of private LTE and 5G deployments, spectrum governance, and regulatory frameworks [1]. Their analytical review highlights radio spectrum as a scarce strategic resource whose efficient allocation largely determines network performance potential. This observation indirectly explains the motivation for reallocating frequencies from obsolete technologies to more advanced radio access layers. However, the study primarily addresses enterprise network scenarios and therefore does not engage with the methodological challenges of phased technology decommissioning in nationwide operator infrastructures.

Bhattacharjee and colleagues analyze spectrum sharing paradigms grounded in cognitive radio concepts for multicast communication [3]. Through systematic evaluation of spectrum allocation mechanisms, the authors demonstrate that effective spectrum governance decisively influences network capacity, energy consumption, and service quality. At the same time, the work does not consider how spectrum sharing principles might be incorporated into operational strategies for retiring legacy network layers.

Manganaris and co-authors propose an algorithmic framework for bandwidth allocation optimization in high-frequency cellular networks using maximum flow algorithms [4]. Simulation results indicate improvements in user coverage and bandwidth utilization under dynamic traffic conditions. The study thus illustrates that network performance during structural transformations depends not only on spectrum volume but also on the efficiency of traffic

distribution algorithms. Nevertheless, it does not address spectrum reallocation between heterogeneous radio technologies within operational networks.

Mir and collaborators evaluate LTE C-V2X communication performance in dense urban vehicular environments [5]. Their simulations reveal that adaptive traffic steering mechanisms significantly enhance reliability and reduce network load compared with static allocation schemes. These results implicitly underscore the importance of intelligent traffic redistribution when users migrate between technology layers. Yet the research remains confined to vehicular communication scenarios rather than nationwide cellular transformations.

Jianxi develops a mathematical model of heterogeneous cellular networks using stochastic topology and Poisson-Voronoi spatial representations [6]. The results demonstrate that irregular spatial models approximate real network structures more accurately than traditional lattice abstractions. While this insight is valuable for evaluating network behavior under structural change, the study offers little guidance regarding the operational process of legacy technology retirement.

Zaid and co-authors review machine learning approaches for handover management in UAV-supported cellular networks [7]. Their analysis indicates that learning-based algorithms can reduce handover failures and enhance communication reliability in high-mobility conditions. Although these findings emphasize the growing relevance of data-driven control mechanisms, the work addresses connection-level mobility optimization rather than large-scale technological transitions.

Salim and colleagues investigate relay-assisted device-to-device communication and resource allocation strategies in next-generation networks [8]. Their review highlights the multidimensional nature of performance optimization, where improvements in one metric may influence several others simultaneously. However, the study does not translate these insights into operational frameworks for coordinated technology phase-out.

Saad and collaborators propose an artificial intelligence–based model for mobility robustness optimization in 5G networks [9]. Simulation results show improvements in handover stability metrics, including reduced ping-pong probability and lower radio link failure rates. Despite these advances, the research does not address system-level consequences of transferring large traffic volumes from legacy technologies to modern radio access layers.

Ma and co-authors analyze energy-efficient resource allocation in heterogeneous cellular networks with wireless backhaul [10]. Their optimization framework demonstrates improved energy efficiency while maintaining service quality constraints. Nevertheless, the study focuses on resource management within existing architectures rather than on structural reconfiguration involving the retirement of obsolete technologies.

Raza and colleagues introduce a machine-learning-based framework for outage detection and recovery in dense cellular networks [11]. Their approach improves fault detection accuracy and accelerates coverage restoration after network failures. Yet the framework is oriented toward reactive resilience management rather than planned technological transitions.

Overall, the reviewed literature confirms substantial progress in understanding cellular network evolution, spectrum utilization, and performance optimization. At the same time, a holistic methodological framework for the strategic retirement of legacy mobile technologies remains conspicuously absent. Most studies emphasize architectural innovation or isolated optimization techniques while largely overlooking the operational logic of phased technology decommissioning. Consequently, an unresolved scientific and engineering challenge emerges: the development of an integrated methodology for retiring legacy cellular technologies in nationwide networks, combining risk assessment, traffic migration modeling, and quantifiable performance evaluation.

The purpose of this article is to develop and experimentally validate a methodological framework for the strategic implementation of UMTS sunset

procedures in national-scale cellular networks. The research aims to formalize the process of legacy radio access technology retirement as a risk-aware optimization problem that simultaneously accounts for traffic migration dynamics, spectrum refarming opportunities, and potential service degradation phenomena.

Presentation of the main research results. The mathematical model proposed in this research emerges from the necessity to formalize the strategic process of UMTS technology retirement in large-scale cellular infrastructures while simultaneously preserving service continuity and maximizing spectrum efficiency. Rather than treating the sunset of a legacy radio access layer as a purely operational action, the model interprets it as a multi-stage optimization process embedded within the broader dynamics of traffic redistribution and spectral refarming. Conceptually, the cellular network is represented as a heterogeneous graph-structured system composed of interconnected radio sites, sectors, and technological layers. Each sector is characterized by a multidimensional state vector that reflects the instantaneous condition of the radio environment, including traffic load, spectral allocation, and quality indicators. In this framework, the network at time moment t can be expressed as a set $N = \{s_1, s_2, \dots, s_n\}$, where each element s_i denotes a sector of the radio access network possessing attributes related to both UMTS and LTE layers.

Within this representation, the total traffic demand observed in a sector constitutes a composite quantity formed by multiple service flows. When the UMTS layer is gradually withdrawn, a portion of this traffic must be redirected toward the LTE infrastructure. The redistribution mechanism can be expressed through the migration function

$$T_i^{\text{LTE}}(t) = T_i^{\text{LTE}}(t-1) + \alpha_i \cdot T_i^{\text{UMTS}}(t-1), \quad (1)$$

where $T_i^{\text{LTE}}(t)$ represents the LTE traffic in sector i after the migration step, $T_i^{\text{UMTS}}(t-1)$ denotes the residual UMTS traffic prior to the sunset operation, and α_i is the migration coefficient reflecting the proportion of users capable of transitioning to LTE coverage. The coefficient itself encapsulates several

environmental parameters such as LTE signal availability, device compatibility, and spectral capacity of neighboring sectors. By embedding these factors into a single adaptive coefficient, the model captures the inherently stochastic character of subscriber behavior during technology migration.

The strategic objective of the sunset process is formulated as the maximization of network performance under constrained risk conditions. This objective can be articulated through the optimization functional

$$\max_S F(S) = \frac{1}{n} \sum_{i=1}^n (w_1 \cdot \Theta_i^{\text{thr}} + w_2 \cdot \Theta_i^{\text{qoe}} - w_3 \cdot R_i), \quad (2)$$

where S denotes the sequence of UMTS sector deactivations, Θ_i^{thr} represents the normalized throughput achieved in sector i , Θ_i^{qoe} corresponds to an aggregated service quality indicator derived from accessibility and retainability metrics, and R_i expresses the risk of service degradation or blackout conditions after migration. The weighting parameters w_1 , w_2 , and w_3 regulate the relative influence of performance gain and operational safety. This formulation deliberately deviates from conventional purely capacity-driven optimization schemes by explicitly incorporating a risk penalty term, thereby transforming the problem into a balanced trade-off between performance improvement and resilience preservation.

A distinctive aspect of the proposed model lies in the explicit representation of blackout risk as a function of sector load and spectral capacity. The probability of overload in a given sector can be approximated by the logistic expression

$$R_i = \frac{1}{1 + e^{-\beta(L_i - C_i)}}, \quad (3)$$

where L_i denotes the projected LTE load after migration and C_i represents the effective LTE capacity determined by available bandwidth and spectral efficiency. The parameter β governs the sensitivity of the overload probability to deviations between demand and capacity. Through this formulation the model introduces a smooth probabilistic transition between stable operation and

congestion scenarios, which more faithfully reflects real network behavior than rigid threshold-based rules.

From a methodological standpoint, the analytical framework also integrates predictive modeling of traffic dynamics. Historical traffic values extracted from the dataset are utilized to construct regression-based forecasting models capable of estimating the expected demand in each sector during the sunset horizon. These forecasts constitute the input parameters for the migration and optimization procedures, thereby allowing the algorithm to anticipate future congestion rather than reacting to it retrospectively. Such anticipatory modeling constitutes a conceptual shift from reactive network optimization toward a predictive paradigm of infrastructure transformation.

The scientific novelty of the proposed model manifests itself in several interrelated dimensions. First, the approach conceptualizes technology retirement not merely as a spectrum management operation but as a formally defined optimization problem that explicitly interlinks traffic migration, spectral refarming, and service reliability. Second, the integration of predictive traffic modeling with risk-aware optimization introduces a methodological bridge between data-driven analytics and strategic radio network planning. Third, the representation of blackout probability through a continuous probabilistic function enables the evaluation of sunset strategies in a nuanced manner that captures the gradual emergence of congestion phenomena rather than treating them as binary events. Finally, the model establishes a coherent analytical foundation upon which simulation experiments can compare alternative sunset strategies and quantify their effects on throughput, service accessibility, and network stability.

Consequently, the mathematical framework developed in this study transforms the traditionally heuristic practice of legacy network shutdown into a rigorously structured analytical process. By articulating the interaction between traffic redistribution, spectral capacity, and probabilistic risk evaluation, the model enables the systematic exploration of alternative technology retirement

trajectories and provides a quantifiable basis for strategic decision making in national-scale cellular networks.

To verify the practical validity and analytical robustness of the proposed mathematical formulation, a dedicated experimental software platform was created. Its primary role is to emulate, within a computational environment, the strategic procedure of gradual UMTS infrastructure retirement across large-scale cellular systems. Rather than serving as a simple simulation script, the developed program operates as a compact analytical environment that integrates heterogeneous network datasets, performs predictive estimation of traffic dynamics, and enables comparative evaluation of alternative transition strategies under controlled experimental conditions.

The developed software environment is implemented in the Python programming language and executed within the Visual Studio Code development ecosystem. The program architecture follows a layered analytical structure that reflects the conceptual logic of the proposed model (fig. 1).

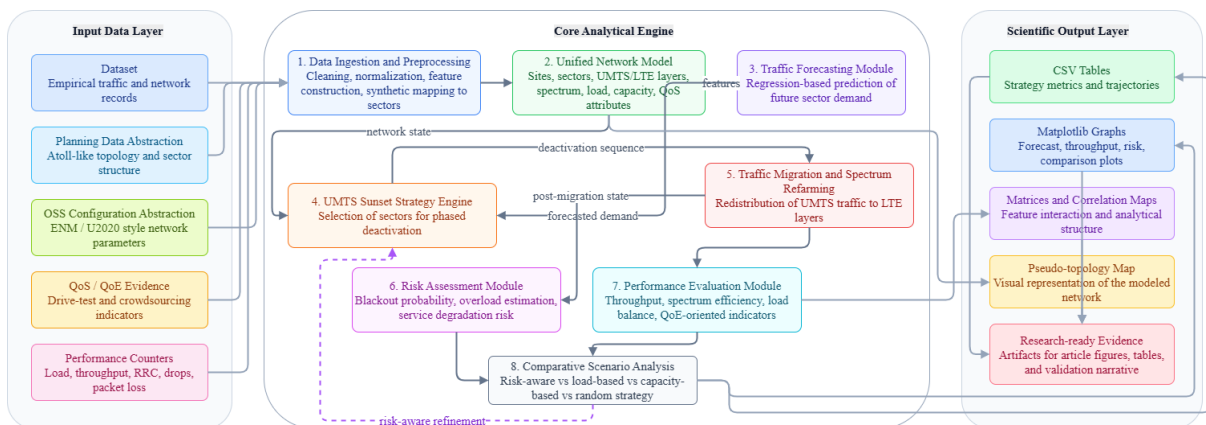


Fig. 1. Experimental Analytical System for Strategic UMTS Sunset Planning

Source: developed by the author

At the foundational layer of the developed system, a data integration module undertakes the ingestion and preliminary transformation of network-related datasets, converting heterogeneous raw records into a coherent analytical representation of the cellular infrastructure. The experimental dataset contains empirical indicators describing traffic distribution and network performance.

Through a chain of preprocessing procedures, these observations are reorganized into sector-level abstractions that reflect individual elements of the radio access network. Each sector is treated as an autonomous analytical unit characterized by attributes such as traffic demand, estimated spectral capacity, projected load dynamics, and indicative quality-of-service parameters.

A notable characteristic of the implementation is the generation of a synthetic yet structurally credible network topology derived from the dataset. Since detailed operator infrastructure data seldom appear in open scientific environments, the system constructs a pseudo-topological representation in which dataset entries correspond to virtual sectors and sites. This procedure yields a graph-like structure approximating the spatial arrangement of radio nodes. Although the resulting topology is not tied to a specific commercial network, it preserves the statistical profile of traffic distribution and therefore provides a plausible experimental substrate for evaluating the proposed model.

The next architectural layer is devoted to predictive traffic analysis. To approximate the temporal trajectory of network demand, the program incorporates machine learning models that estimate future traffic volumes using historical observations. Several regression-based predictors generate alternative forecasts that approximate the expected redistribution of traffic following the withdrawal of the UMTS layer. In effect, this module converts static measurements into a dynamic representation of demand during the technology sunset process.

The computational nucleus of the program is a simulation module reproducing successive phases of technology retirement. The network state evolves through discrete iterations, each corresponding to the deactivation of a subset of UMTS sectors selected according to a particular decision strategy. After deactivation, the traffic formerly served by UMTS is redirected to LTE infrastructure following the migration mechanism formulated in the mathematical model. This redistribution alters load patterns across neighboring sectors and consequently affects performance indicators throughout the network.

Embedded within this module is a strategy evaluation engine. Instead of relying on a single deterministic rule, the system explores several alternative approaches to network transformation, including heuristic load-driven decisions, capacity-oriented allocation mechanisms, stochastic baseline procedures, and a risk-aware algorithm derived from the model formulation. Each strategy produces a distinct sequence of sector shutdowns and, consequently, a different pattern of traffic migration. Running these strategies under identical initial conditions establishes a comparative analytical environment in which their structural consequences can be observed.

During each simulation iteration, the system continuously evaluates the evolving network state. Analytical indicators are computed for every sector to estimate operational conditions after traffic redistribution. These indicators include approximations of throughput, spectral utilization, congestion probability, and service availability. Rather than applying rigid deterministic thresholds, the program relies on probabilistic estimations of overload risk in sectors experiencing excessive demand. This approach allows the simulation to capture gradual degradation of network performance instead of abrupt failure events.

Another architectural element is the analytical reporting subsystem, whose role is to translate numerical simulation outcomes into interpretable analytical artifacts. After completing simulation cycles, the system automatically produces graphical representations and statistical matrices illustrating the progression of network behavior throughout the sunset process. The generated outputs include comparative traffic forecasts, sector correlation matrices, pseudo-geographical topology maps, and diagrams reflecting the evolution of network indicators across strategy scenarios. These artifacts are exported as image files and structured datasets, enabling their direct integration into research documentation.

A further design principle of the system is its modular structure. The principal components – data integration, predictive modeling, simulation execution, and analytical reporting – operate as loosely coupled computational

blocks connected through a shared data representation. Such decomposition provides substantial experimental flexibility: forecasting models may be replaced, migration functions refined, or decision strategies modified without disturbing the overall architecture. From a methodological perspective, this modularity improves transparency and reproducibility of the computational experiment.

Ultimately, the developed software system represents a computational embodiment of the theoretical model, translating abstract mathematical constructs into an executable experimental environment. By combining empirical datasets, predictive traffic modeling, and iterative simulation of technology retirement scenarios, the platform enables systematic exploration of the interplay between traffic migration, spectral capacity, and service reliability. In doing so, it provides a practical analytical instrument for assessing how alternative strategies of UMTS sunset may influence the structural dynamics of large-scale cellular networks.

The experimental evaluation utilized an open dataset describing performance characteristics of wireless cellular environments [13], which contains empirical measurements of signal strength (-50 to -120 dBm), distance between user equipment and base stations, signal-to-noise ratio, and signal attenuation. These parameters, obtained through spectrum analyzers, GPS-assisted distance estimation, and radio propagation measurements, collectively capture essential indicators of radio link quality and network behavior. Within this research, the dataset was repurposed as an empirical substrate for constructing an abstract sector-level representation of radio conditions in a simulated cellular network. Although not tied to a specific operator infrastructure, its statistical properties provide a plausible approximation of real propagation and coverage dynamics, thereby enabling estimation of link reliability, coverage quality, and potential traffic redistribution effects during the gradual withdrawal of a legacy radio layer in the proposed analytical model [13].

The proposed analytical concept was validated through computational experiments performed within a purpose-built simulation environment. This

experimental setup enabled the exploration of practical implications associated with the gradual withdrawal of UMTS infrastructure and the subsequent redistribution of traffic flows toward LTE layers. The resulting observations reveal how key performance characteristics of the cellular network evolve under alternative sunset scenarios and provide a grounded basis for evaluating the practical efficiency of the introduced risk-aware optimization approach.

At the preliminary phase of the study, an artificial spatial model of the cellular network was generated to approximate how radio sectors are distributed and how legacy UMTS traffic is unevenly concentrated across the infrastructure. The synthesized topology is presented in Fig. 2. In this representation, sector positions are mapped within a virtual coordinate space, while the size and color of the markers visually indicate the relative share of UMTS traffic processed by each sector.

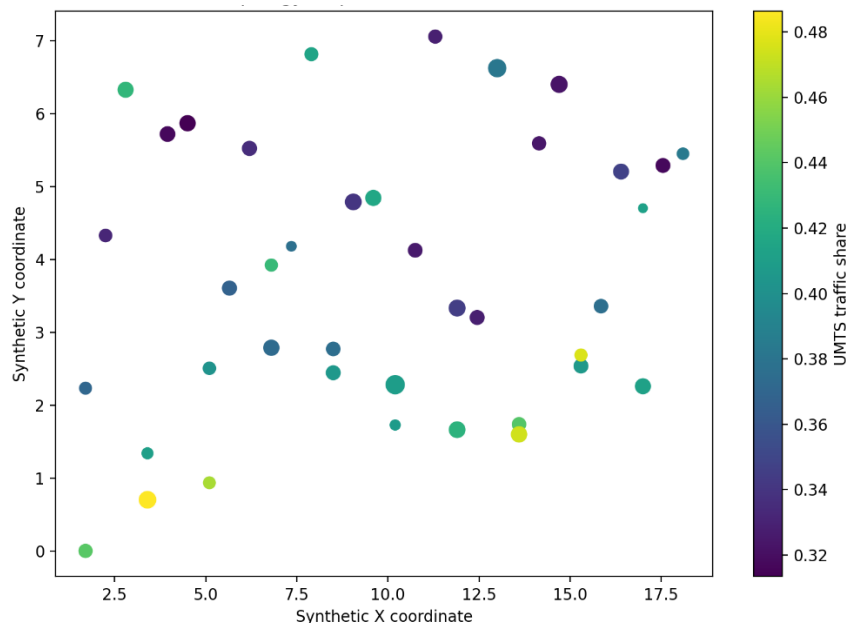


Fig. 2. Pseudo-topology representation of cellular sectors and UMTS traffic burden

Source: developed using the author's proprietary software

Such representation provides a conceptual visualization of heterogeneous traffic conditions typically encountered in real mobile networks, where certain cells continue to carry a significant legacy traffic share while others already operate predominantly on LTE layers. The visualization reveals a non-uniform

distribution of UMTS load, which substantiates the necessity of a selective and strategically orchestrated sunset process rather than an indiscriminate deactivation of legacy infrastructure.

A deeper insight into the structural relationships between the engineered sector-level parameters is presented in fig. 3, which depicts the correlation matrix of radio and traffic indicators derived from the dataset.

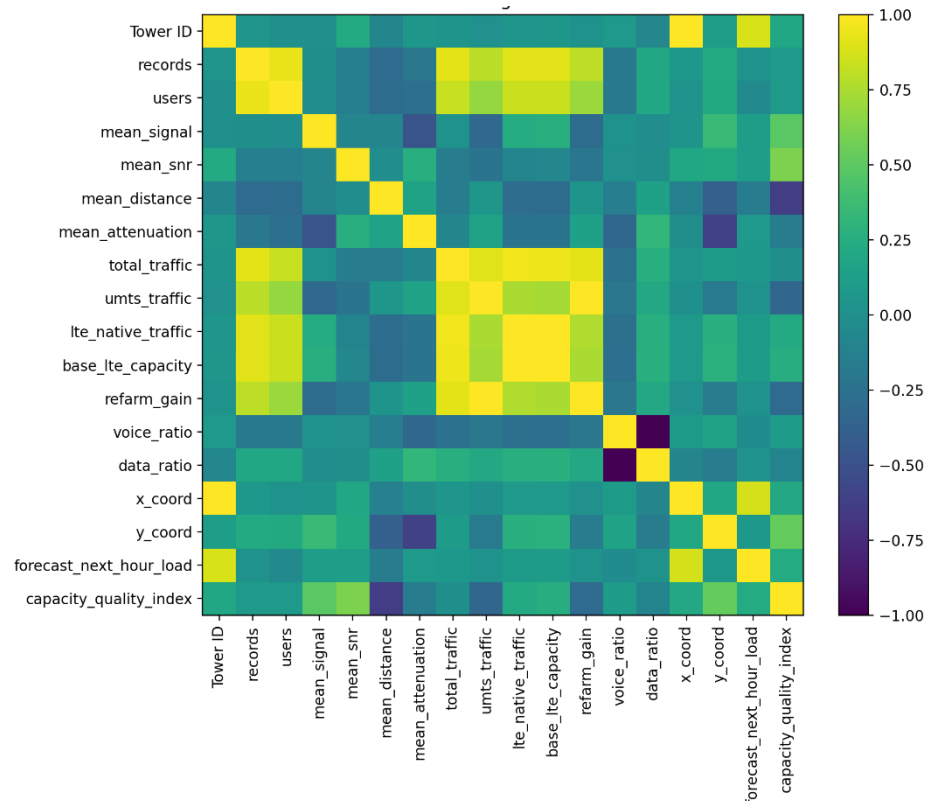


Fig. 3. Correlation matrix of engineered sector-level radio and traffic features

Source: developed using the author's proprietary software

Several meaningful statistical relationships emerge from the analysis. In particular, indicators describing the number of users, overall traffic intensity, LTE-originated traffic, and baseline LTE capacity display pronounced positive correlations. Such behavior naturally reflects the operational logic of cellular systems, where increasing demand is typically accompanied by proportional growth of network capacity. In contrast, variables related to signal attenuation and transmission distance reveal inverse associations with signal strength metrics, which corresponds to the fundamental physics of radio wave propagation.

Altogether, the observed correlation pattern suggests that the constructed feature space adequately reproduces realistic characteristics of cellular radio environments and therefore provides a credible foundation for subsequent analytical modeling.

The central objective of the proposed model consists in evaluating how different UMTS sunset strategies influence the evolution of LTE network performance. The dynamics of the average LTE throughput during progressive shutdown of UMTS sectors are depicted in fig. 4.

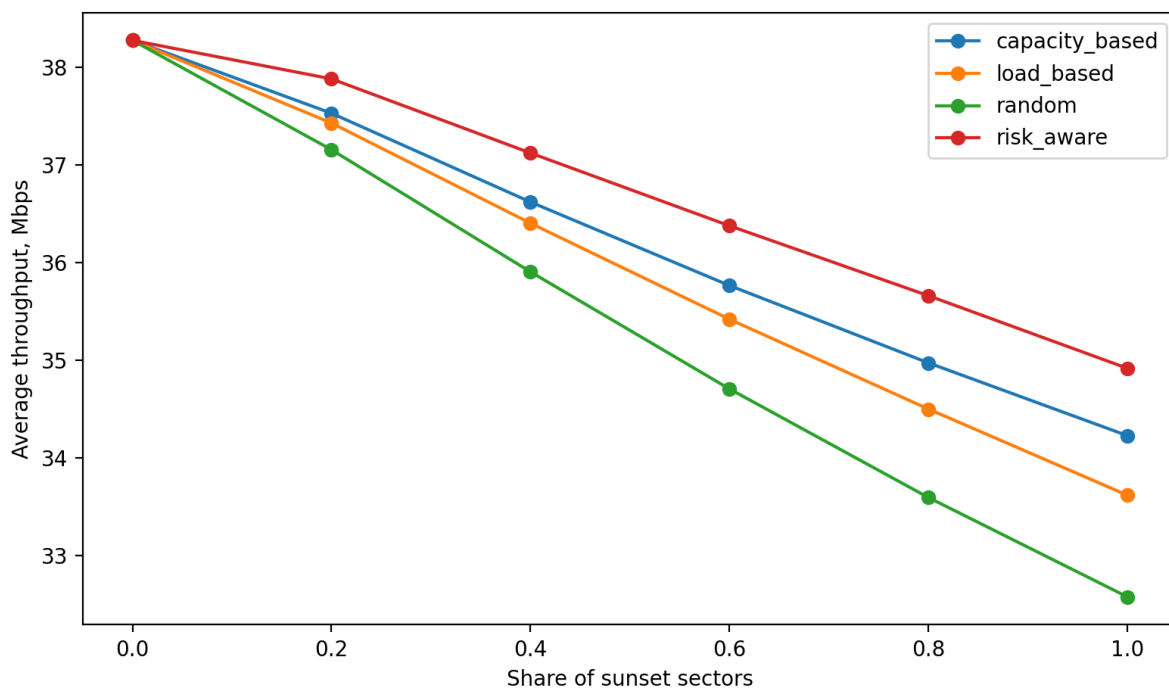


Fig. 4. Evolution of average LTE throughput across progressive UMTS sunset stages

Source: developed using the author's proprietary software

The results reveal a gradual decline of average throughput as the share of sunset sectors increases, which reflects the inevitable increase in LTE traffic load caused by subscriber migration. However, the magnitude of this degradation varies considerably depending on the applied strategy. The risk-aware approach consistently demonstrates the most resilient throughput trajectory, preserving higher performance levels even when a substantial fraction of UMTS infrastructure has already been deactivated. By contrast, the random strategy

exhibits the steepest decline in throughput, which illustrates the inefficiency of uncoordinated infrastructure shutdown procedures.

An additional dimension of network stability is captured through the analysis of blackout risk, which reflects situations where LTE capacity becomes insufficient to accommodate redirected traffic flows. The evolution of blackout occurrences across sunset stages is presented in Fig. 5.

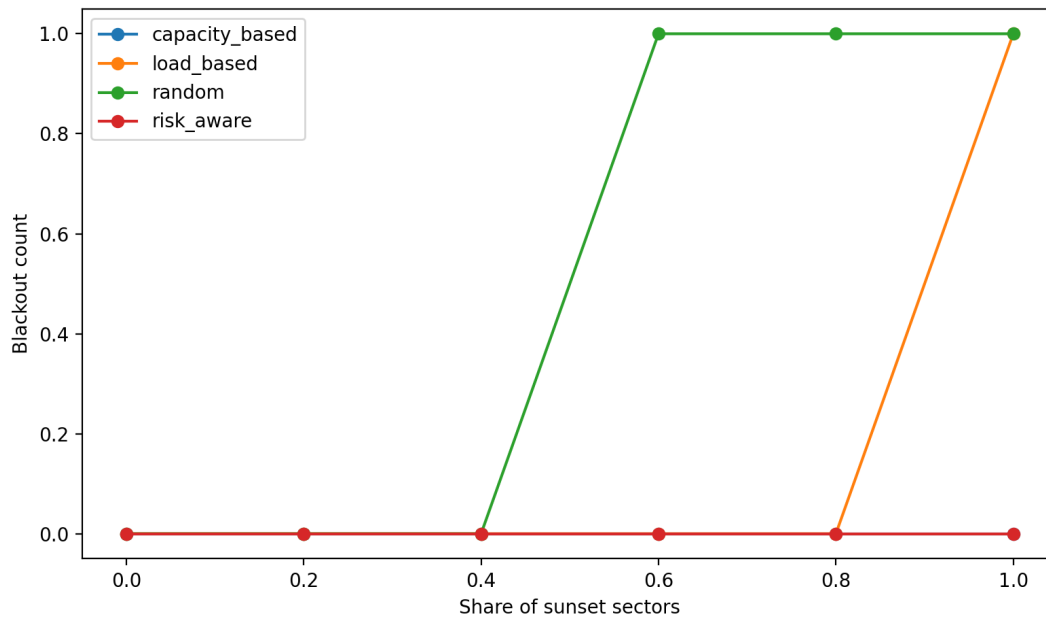


Fig. 5. Trajectory of blackout risk under different UMTS sunset strategies

Source: developed using the author's proprietary software

The results indicate that the risk-aware strategy effectively suppresses blackout events throughout the entire transition process. In contrast, both the load-based and random strategies eventually trigger blackout situations when the share of decommissioned UMTS sectors exceeds certain thresholds. These results demonstrate that purely load-driven or stochastic shutdown decisions fail to adequately account for capacity redistribution effects within the radio access network.

The cumulative effect of these phenomena is summarized in fig. 6, which compares the final number of blackout occurrences across all evaluated strategies.

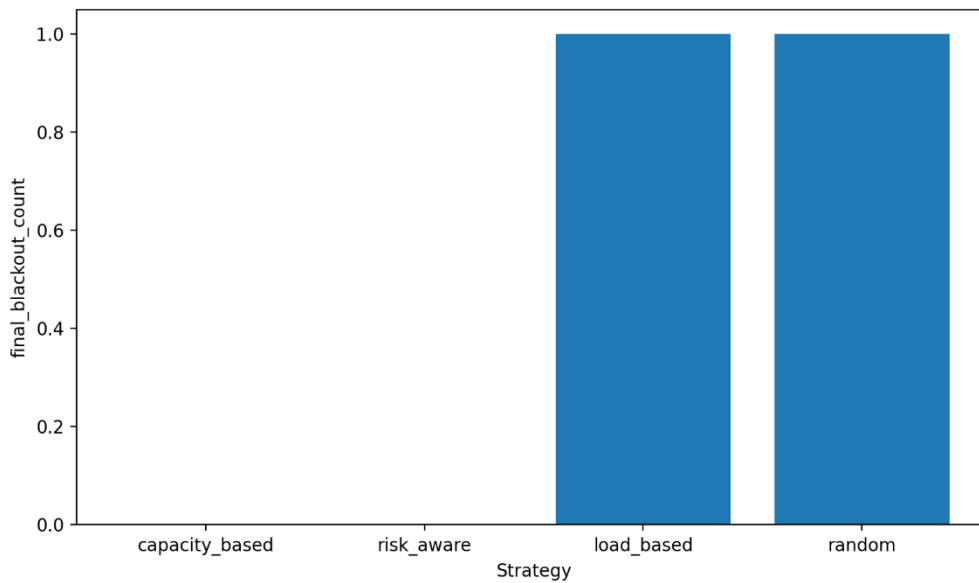


Fig. 6. Comparison of final blackout occurrence across sunset strategies

Source: developed using the author's proprietary software

The results clearly demonstrate that the proposed risk-aware methodology completely eliminates blackout events under the examined conditions, whereas the alternative strategies exhibit residual failure scenarios. This outcome highlights the importance of explicitly incorporating risk estimation mechanisms into sunset planning procedures.

Beyond network availability, the proposed model also evaluates the impact of the transition process on signaling performance. The final RRC connection success rate, presented in fig. 7, remains consistently high across all strategies, with only marginal variations.

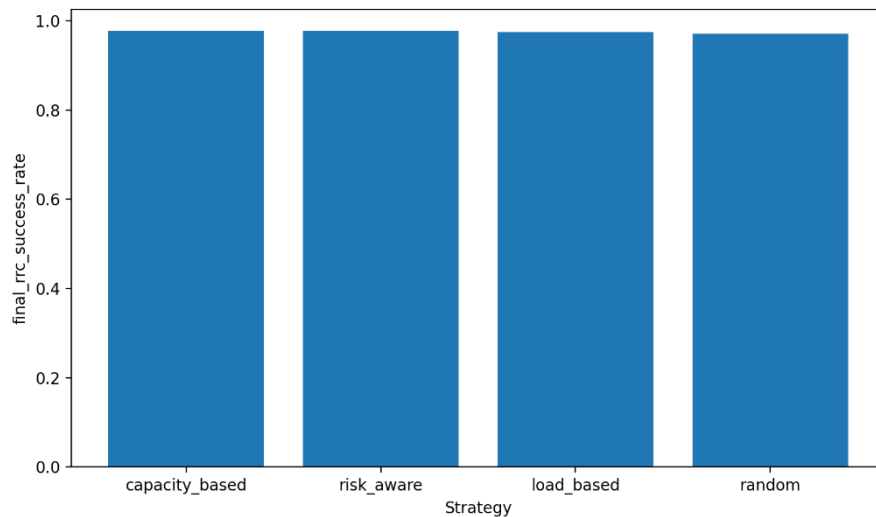


Fig. 7. Final RRC connection success rate across alternative sunset strategies

Source: developed using the author's proprietary software

Such stability indicates that the simulated LTE infrastructure retains sufficient signaling robustness even under elevated traffic loads. Nevertheless, the slightly higher success rate observed under the risk-aware strategy suggests that the proposed method contributes to maintaining signaling reliability by preventing localized overload conditions.

The aggregate throughput results at the final stage of the transition are presented in fig. 8.

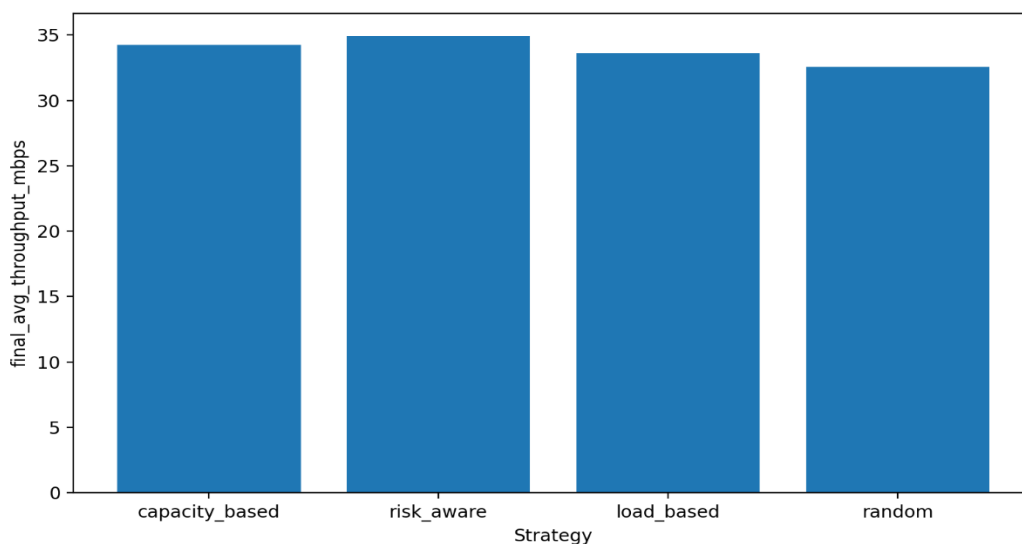


Fig. 8. Comparison of final average LTE throughput achieved by different sunset strategies

Source: developed using the author's proprietary software

These results reinforce the conclusions drawn from the throughput trajectories. The risk-aware strategy achieves the highest final throughput value, followed closely by the capacity-based approach, whereas the load-based and random strategies exhibit lower performance. This ranking indicates that the proposed algorithm more effectively balances traffic redistribution and spectrum refarming, thereby maximizing the utilization efficiency of LTE resources.

An additional component of the analytical framework involves anticipating traffic patterns that may emerge during the migration phase. The relative effectiveness of the forecasting approaches employed in the study is presented in fig. 9.

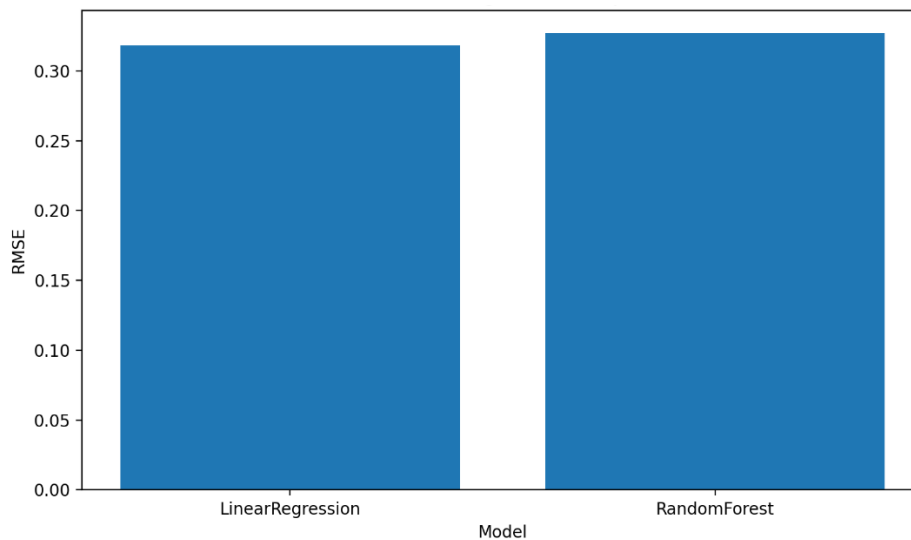


Fig. 9. Performance comparison of traffic forecasting models based on RMSE

Source: developed using the author's proprietary software

The linear regression model demonstrates slightly lower prediction error compared to the random forest approach in terms of RMSE. This somewhat counterintuitive result suggests that the examined traffic patterns can be sufficiently captured by relatively simple linear relationships, which may reflect the moderate complexity of the synthesized dataset. Consequently, the forecasting component of the proposed system can rely on computationally lightweight models without sacrificing predictive accuracy.

Collectively, the observed outcomes confirm the practical viability of the proposed mathematical model together with the analytical system built around it. The experiments demonstrate that incorporating risk-aware decision mechanisms into the UMTS sunset planning process significantly improves the stability of the network during technological transition. The proposed approach successfully minimizes blackout risk, preserves higher LTE throughput levels, and maintains robust signaling performance throughout the migration process.

From a broader perspective, the results confirm that the developed analytical framework can serve as a practical decision-support instrument for mobile network operators facing large-scale technology migration challenges. By integrating traffic forecasting, capacity modeling, and risk evaluation into a unified analytical environment, the proposed system enables a more deliberate and scientifically grounded approach to infrastructure evolution. Consequently, the proposed methodology represents a viable and operationally advantageous strategy for orchestrating UMTS sunset operations in contemporary cellular networks.

Conclusions and future research. The study demonstrates that the retirement of UMTS infrastructure can be systematically analyzed as a multi-stage optimization problem that incorporates traffic migration, spectrum refarming, and operational risk. The proposed analytical framework combines mathematical modeling, predictive traffic estimation, and simulation-based evaluation, transforming legacy technology shutdown from a heuristic engineering decision into a structured analytical process.

Simulation experiments show that the risk-aware sunset strategy provides the most stable transition scenario. Under the tested conditions, this approach completely eliminated blackout events, while load-based and random shutdown strategies generated network failures when the share of decommissioned sectors increased. At the same time, the risk-aware method preserved higher LTE throughput levels throughout the transition, whereas stochastic shutdown

produced the strongest performance degradation. The LTE signaling layer remained stable across scenarios, maintaining a high RRC connection success rate. Additionally, the traffic forecasting component demonstrated that a linear regression model achieved lower RMSE than a random forest predictor, indicating that relatively simple models can adequately approximate migration dynamics.

Future research should focus on validating the framework using real operator datasets, incorporating spatial mobility patterns of subscribers, and extending the model toward multi-objective optimization that includes economic and energy-efficiency indicators.

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