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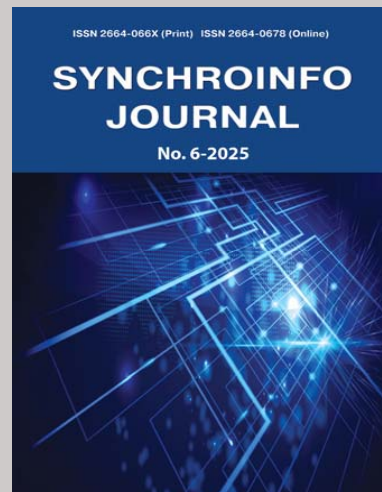
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# EMC IMPLICATIONS OF FREQUENCY-DEPENDENT GROUNDING IMPEDANCE IN INDUSTRIAL AUTOMATION EQUIPMENT

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## ABSTRACT

This paper presents a quantitative model of induced voltage in power supply cables of industrial equipment, focusing on the shielding effectiveness provided by the cable screen (PE conductor) as a function of its grounding resistance and the frequency of the disturbing magnetic field in the range up to 10 kHz. Based on a quasi-stationary three-conductor approximation with dominant inductive coupling, the analytical expression reveals a sharp threshold behavior: induced voltage magnitude remains low only at very small grounding resistances (1-4  $\Omega$  at power frequency). At audio and higher frequencies (0.8-10 kHz), shielding efficiency degrades markedly due to the growing inductive reactance of the "screen-ground" drainage path, rendering compensation ineffective even at resistances still considered acceptable under some 50 Hz norms (up to 30  $\Omega$ ). Numerical results for grounding resistances spanning 0.1  $\Omega$  to 100 M $\Omega$  and selected frequencies explain several persistent field observations: seasonal surges in failures of CNC electronics and control modules during periods of elevated soil resistivity (drought, freezing), damage to microcontrollers, power switches, and input circuits despite conventional overcurrent protection, and limited success of localized mitigation when long parallel cable routes act as open inductive loops. The study emphasizes that grounding impedance must be regarded as strongly frequency-dependent. Reliable electromagnetic immunity in industrial environments, where soil resistivity often ranges from 500 to 5000  $\Omega\cdot\text{m}$  or higher, requires low-impedance designs across the relevant spectrum: extended electrode configurations (multiple rods, grids, deep wells), ground enhancement materials, rational cable routing, consistent shielded cabling, staged surge protection with minimized inductance, and, where practical, fiber-optic interfaces. In multilayered soils typical of industrial sites, accurate high-frequency prediction necessitates Wenner/Schlumberger measurements followed by layered inversion modeling. The findings advocate a systemic approach to EMC rather than isolated fixes. Future investigations will target optimized grounding topologies for high-resistivity soils, inclusion of distributed parameters at tens of kHz, detailed multilayer simulations, and field verification.

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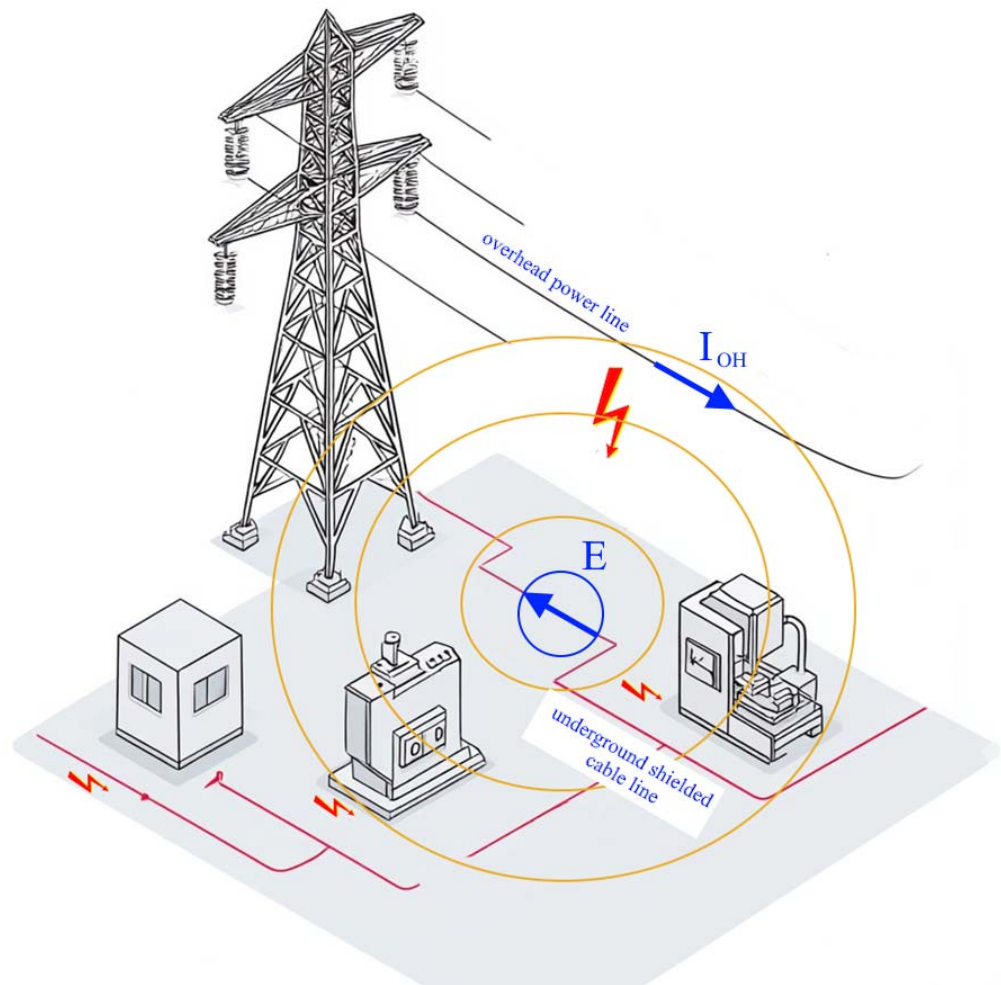


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**KEYWORDS:** *electromagnetic compatibility, EMC, grounding, induced voltage, CNC, machine tool industry, industrial equipment, industrial automation.*

## 1 Introduction

The integration of digital technologies into manufacturing significantly increases the dependence of computer numerical control (CNC) machines and other automated systems on the electromagnetic immunity of their electronic components. Field measurements and laboratory tests [1, 2] indicate that a substantial proportion of electronic equipment failures in industrial environments result from impulsive overvoltages as well as deficiencies in grounding and equipotential bonding systems. According to various sources, such failures may account for up to 60 % of all incidents related to power quality and electromagnetic compatibility (EMC) [3, 4]. The main pathways for the penetration of induced voltages into power supply cable lines of industrial equipment are illustrated in Figure 1.



**Figure 1.** Penetration of extraneous voltages into the power supply cable line

The siting of production facilities in industrial areas necessitates consideration of several key factors. First, equipment, including CNC systems, electronics, longitudinal automation lines, and power supply networks, is exposed to intense electromagnetic fields generated by high-voltage transmission lines and traction power systems. Second, the upper soil layers near the facilities often exhibit high specific resistivity, which complicates the design and construction of effective grounding systems.

Precisely under such conditions, traditional grounding approaches, such as standard vertical electrodes 3-6 m in length, horizontal strips, and similar configurations, frequently prove either ineffective or economically unjustifiable. This highlights the pressing need to develop optimal solutions that are both technically efficient and resource-saving [5].

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Modern design of industrial facilities demands a comprehensive consideration not only of primary energy supply technologies but also of a thorough elaboration of all auxiliary engineering systems, including grounding and lightning protection arrangements. As emphasized in study [6], the effectiveness of design solutions directly depends on the quality of geotechnical investigations, the correctness of the selected grounding scheme, the reliability of soil property assessments, and strict adherence to applicable normative requirements.

Modern practice demonstrates that analyzing electromagnetic disturbances solely at the fundamental frequency of 50 Hz is insufficient. In actual operating conditions of power systems and traction networks, a significant portion of the energy is concentrated in the kilohertz range due to harmonics, switching transients, magnetization inrush currents, fault conditions, and fast transients that are not adequately limited by conventional overcurrent protective devices [2, 3].

In [6], it is shown that classical methods fail to account for the spectral characteristics of influencing lines; accordingly, a mathematical model for railway infrastructure in phase coordinates was proposed, based on a system of differential equations solved in the Laplace domain.

The issue of electromagnetic influences extends beyond cable lines alone. Digital models have been developed for the electromagnetic effects of multi-wire traction networks (25 kV) and overhead power lines on parallel pipelines, taking into account actual train movement profiles, phase current distributions, and distributed pipeline grounding [7]. It was found that under typical operating conditions, maximum induced voltages reach 300-700V far exceeding the 60V safety limit, while in fault scenarios on 220 kV lines (single-phase short circuits), voltages can rise to several kilovolts at structure extremities.

In paper [8], the authors examine practical aspects of transitioning from electromechanical relays to microprocessor-based relay protection and automation devices (MPRPD) at substations. MPRPDs are considerably more susceptible to transient and high-frequency disturbances (lightning strikes, switching overvoltages, single-phase-to-ground faults), which, in the absence of adequate EMC measures, lead to malfunctions, false tripping, and commissioning delays. Emphasis is placed on grounding architecture (separation of power and secondary grounding loops, shielding, foundation grids) and the limitations of retrofitting legacy substations.

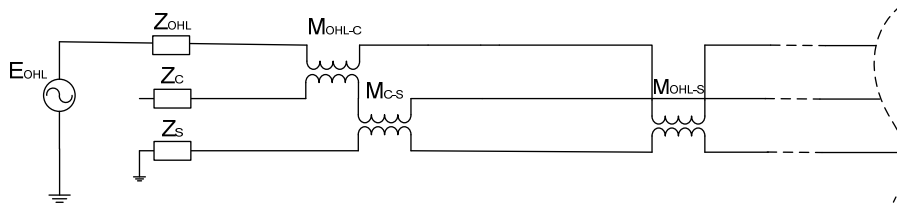
The theoretical basis for inductive coupling calculations rests on models that include earth-return currents, multi-conductor equivalent circuits, and geometry- and soil-dependent mutual inductances [9, 10]. A decisive factor is the frequency-dependent impedance of disturbance current paths in the grounding system: at 50 Hz, resistive spreading dominates, but in the range up to 10 kHz, the inductance of PE conductors prevails, causing a sharp rise in residual overvoltages at equipment inputs [11, 12]. Therefore, core EMC, measures shielding, cable routing, and grounding, must be analyzed with respect to the actual spectral content of electromagnetic fields, taking into account parallel route length and separation, the mutual inductance matrix, and line parameters [13, 14].

Spectral analysis of currents and voltages in power and traction networks shows considerable electromagnetic energy in the band up to 10 kHz during switching operations, fault disconnections, and high-power converter activity [1-3]. Even when regulatory clearance zones around power facilities are respected, long power and signal cables inevitably create conductive loops and common-mode paths that remain continuously exposed to electromagnetic fields. Minimum horizontal separation distances from overhead line conductors provide electrical safety and operational reliability but do not prevent inductive coupling into extended metallic structures and cables located beyond these zones [15]. In such conditions, the primary controllable parameter for electromagnetic immunity is the frequency-dependent impedance of the grounding and equipotential bonding system, which ultimately determines disturbance currents and voltages at the inputs of sensitive modules during common-mode events [18].

The objective of the present study is to quantitatively characterize the dependence of induced voltage in a power line on the grounding resistance of the cable screen (PE conductor) and the frequency of the disturbing source in the range of 50 Hz to 10 kHz, thereby substantiating practical recommendations for the operation of CNC machines and automated industrial equipment.

## 2 Methods

The model is based on a quasi-stationary three-conductor equivalent circuit shown in Figure 2. Within this framework, the electromagnetic influence of an overhead power line (OHL) on the core (C) of an underground shielded cable line is considered over a section of length  $l$ . The influencing line represents the nearest power feeder or a parallel cable line. The shield (S) corresponds to the metallic sheath of the cable with equivalent impedance  $Z_s$ , grounded at both ends of the section. In the present study, the affected line is taken as the phase conductor supplying power to an electronic module, referenced to ground (earth) as the return path.



**Fig. 2.** Equivalent circuit of a single-conductor shielded line under magnetic influence

The mathematical description of the propagation of currents and voltages induced by magnetic coupling in each conductor is provided by a system of differential equations, the order of which depends on the number of conductors forming the unified electromagnetic system. For the power supply cable line under consideration consisting of the core and the shield the system comprises four equations:

$$\begin{cases} \frac{dU_C}{dx} = (R_C \quad C) \cdot I_C \quad M_{C-S} \quad M_{C-OHL} \cdot I_{OHL} \cdot e^{-\gamma x}, \\ -\frac{dI_C}{dx} = (G_C \quad C_C) \cdot U_C + (G_{C-S} \quad C_{C-S}) U_S, \\ -\frac{dU_S}{dx} = (R_S \quad R_{ground} \quad S) \cdot I_S \quad M_{C-S} \quad M_{S-OHL} \cdot I_{OHL} \cdot e^{-\gamma x}, \\ -\frac{dI_S}{dx} = (G_S \quad C_S) \cdot U_S + (G_{C-S} \quad C_{C-S})(U_S \quad U_C). \end{cases} \quad (1)$$

where  $R_k, L_k, G_k, C_k$  are the self-parameters of the  $k$ -th conductor;

$M_{i-k}, G_{i-k}, C_{i-k}$  are the mutual parameters between the  $i$ -th and  $k$ -th conductors, computed across the frequency spectrum;

$U_k, I_k$  are the voltages and currents in the respective conductors.

Equation system (1) enables a rigorous derivation of the induced voltage on the core as a function of the frequency of the external electromagnetic field and the shield grounding resistance. Since inductive coupling dominates in the low-frequency range of 50 Hz to 10 kHz, capacitive coupling and distributed effects are neglected. Thus, the magnitude of the core EMF can be expressed as:

$$E_C = j\omega I_{OHL}(M_{OHL-C}) - j\omega I_S(M_{C-S}) \quad (2)$$

The shield current is governed by the loop equation:

$$j\omega I_{OHL}(M_{OHL-S}) = I_S(R_S + R_{ground} + j\omega L_S) \quad (3)$$

Consequently, the induced voltage on the core as a function of frequency and grounding resistance takes the form:

$$E_C(\omega, R_{ground}) = j\omega I_{OHL}(M_{OHL-C}) - j\omega(M_{C-S}) \cdot j\omega I_{OHL}(M_{OHL-S}) / (R_S + R_{ground} + j\omega L_S) \quad (4)$$

The grounding resistance of a single vertical electrode, accounting for the climatic seasonality coefficient of soil resistance, is determined by the following expression [17]:

$$R_{ground} = k \cdot \frac{\rho}{2\pi L} \ln \left( \frac{2L}{d} \right) \cdot \left( 0.5 \ln \frac{4t+L}{4t-L} \right), \quad (5)$$

where  $k_1$  is the frost penetration coefficient, which accounts for seasonal variations in soil temperature;  $L$  is the electrode length, m;  $\rho$  is the soil resistivity,  $\Omega \cdot m$ ;  $t$  is the depth from the ground surface to the midpoint of the electrode, m;  $d$  is the electrode diameter, m.

The selection of electrode parameters is performed to ensure compliance with the normative grounding resistance values as required by applicable standards [18], while also considering the geological structure of the soil, the density of infrastructure in the installation area, and techno-economic criteria.

In industrial zones, soil resistivity is the decisive factor in determining the type, configuration, and dimensions of grounding systems, as it directly governs the current spreading resistance and the surface potential gradient. Under typical industrial site conditions (factories, substations, CNC-equipped workshops, and power-intensive facilities), soil resistivity values vary over a wide range: from 10-150  $\Omega \cdot m$  in marshy and moist loamy soils to 1000-5000  $\Omega \cdot m$  (and occasionally up to 40 k $\Omega \cdot m$ ) in dry sandy, rocky, stony, or made-ground areas commonly found on industrial premises. High soil resistivity significantly impairs the dissipation of short-circuit currents, impulsive overvoltages, and lightning discharges, resulting in elevated ground potential rise and increased step and touch voltages. Seasonal fluctuations in  $\rho$  necessitate a conservative design approach: calculations must be based on worst-case conditions, supplemented by regular periodic monitoring of grounding resistance.

Thus, accurate determination of soil resistivity during the geotechnical survey stage not only ensures compliance with electrical safety requirements but also enables optimization of material costs by avoiding both underestimation of risks (unsafe conditions) and overdesign (excessive expenditure) of the grounding system.

### 3 Results

Due to range of soil resistivity the grounding resistance  $R_{\text{ground}}$  was varied numerically from 0.1  $\Omega$  to 100 M $\Omega$ , covering operational conditions from normative-compliant grounding devices to degraded or faulted states. Figure 3 presents the calculated dependence of the grounding resistance  $R_{\text{ground}}$  on soil resistivity  $\rho$  for a single vertical electrode of length 3m and diameter 16 mm.

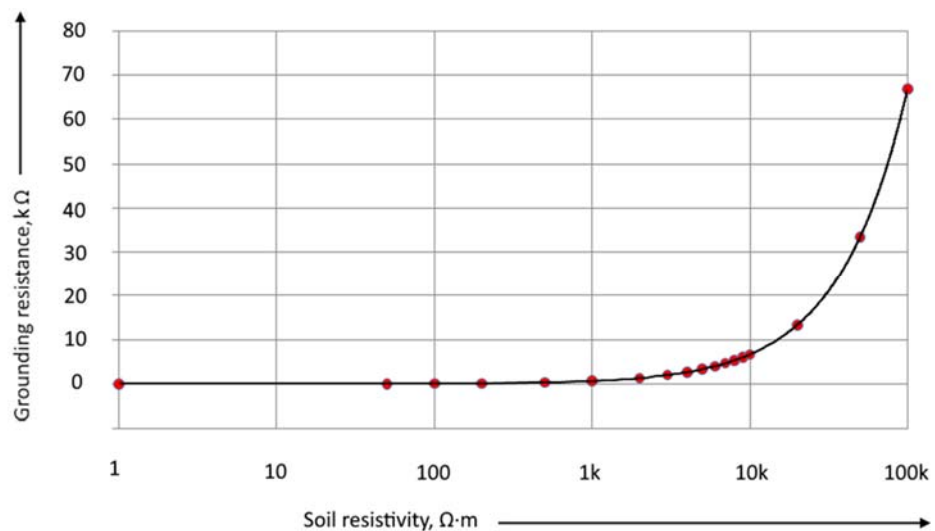


Fig. 3. Grounding resistance  $R_{\text{ground}}$  on soil resistivity  $\rho$

External disturbances were interpreted using standardized test models from the IEC 61000 series, which provide representative spectral energy distributions up to 10 kHz for industrial environments, as well as industry-specific guidelines for protection of communication lines near traction networks, indicating significant induced voltages on parallel conductors tens of meters from the source [16]. Practical separation distances from influencing overhead lines were referenced to the clearance zone norms for electric

power facilities [11]. EMC requirements were considered in the context of core industrial immunity standards, surge protective device coordination, and grounding system architectures [16].

The numerical parameters used in the modeling are presented in Table 1. The values are normalized to the orders of magnitude typical for real extended parallel routings in order to reveal threshold effects.

Table 1

Parameters for numerical modeling

Parameter	Value
Mutual inductance $M_{OHL-C}$ (influencing line – core)	3 mH
Mutual inductance $M_{OHL-S}$ (influencing line – shield)	4 mH
Mutual inductance $M_{S-C}$ (shield – core)	30 mH
Inductance of the shield loop $L_S$	33 mH
Shield resistance $R_S$	3.4 $\Omega$

The computation results are presented in Fig. 4. For an influencing line current magnitude of  $|I_{OHL}| = 1$  A at 50 Hz, the induced voltage magnitude on the core  $|U_C|$  as a function of grounding resistance  $R_{ground}$  increases monotonically, showing a distinct inflection point when transitioning from the region of low resistances to moderate values. At grounding resistances on the order of 0.1-1  $\Omega$ , the shield current is high, and its phase is close to providing nearly quadrature compensation of the induced EMF. At  $R_{ground}$  up to 4  $\Omega$ , a noticeable increase in  $|U_C|$  becomes apparent, followed by a steep section of the curve in the 4-30  $\Omega$  interval, after which the shielding effectiveness drops sharply. In the grounding resistance range of 30  $\Omega$  to 100 M $\Omega$ , the shielding effect is negligible.

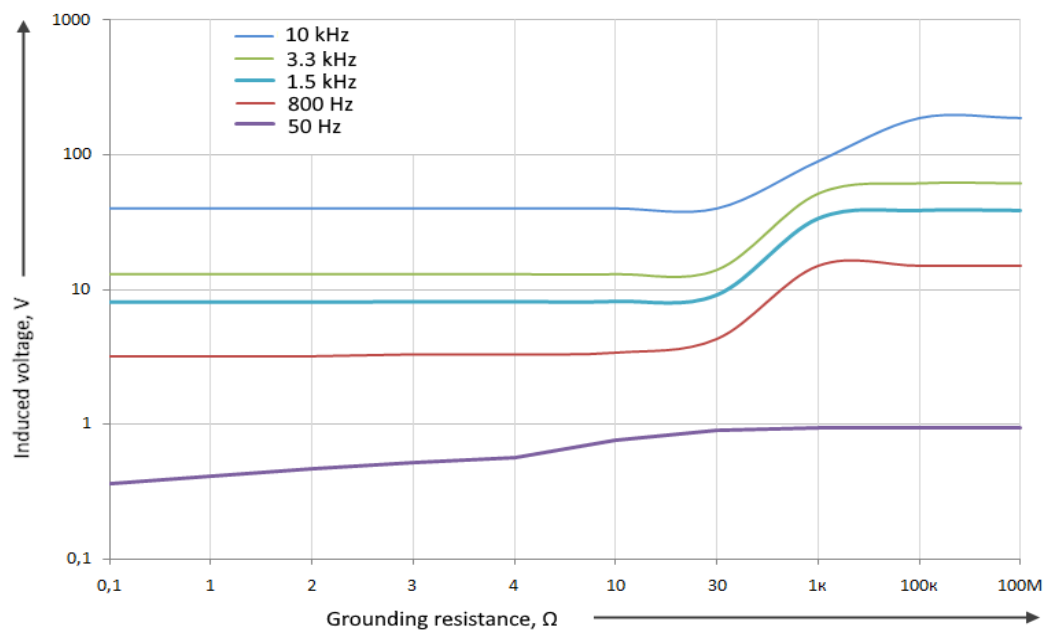
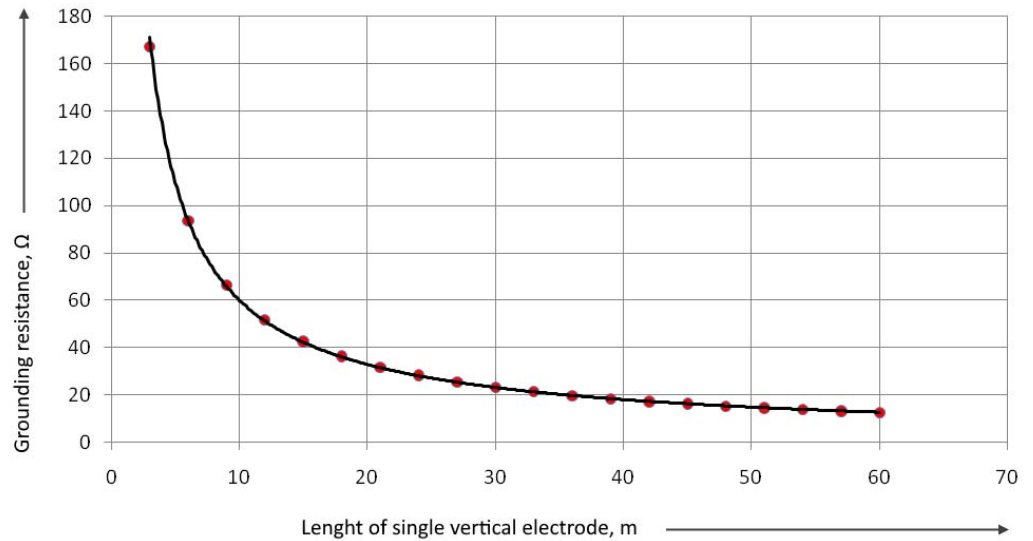


Fig. 4. Calculated dependence of the induced voltage on grounding resistance across the frequency spectrum

In the audio-frequency band (0.8–3.3 kHz), the highest shielding effectiveness is achieved at grounding resistances up to 30  $\Omega$ , whereas at resistances above 1 k $\Omega$  the shielding effect is virtually absent. As the frequency of the influencing current rises, the protective performance of the shield further deteriorates. For example, at 10 kHz, an avalanche-like increase in induced voltage is observed up to grounding resistance values as high as 100 k $\Omega$ , indicating an emergency (fault) operating condition of the grounding system (given the normative requirements of 2 to 30  $\Omega$  [11]).

To evaluate the feasibility of achieving the required grounding resistance for effective shielding (not exceeding  $30 \Omega$ ), fig. 5 presents the calculated dependence of the grounding resistance of a single vertical electrode on its length (midpoint burial depth  $t = L/2$ , climatic coefficient  $k_1 = 1$  (reference non-frozen condition) and soil resistance is  $500 \Omega$ ).



**Fig. 5.** Grounding resistance on the length of a single vertical electrode

The results demonstrate that, under such soil conditions, even a relatively long single electrode ( $L = 10 \text{ m}$ ) yields  $R \approx 60 \Omega$ , while  $L = 20 \text{ m}$  still gives  $\approx 35 \Omega$ . Achieving  $R \leq 30 \Omega$  would require an impractically long rod well over  $25 \text{ m}$  in most realistic scenarios.

#### 4 Discussion

Equation (4) reflects the presence of two opposing mechanisms: the primary induced EMF in the core increases proportionally to  $\omega$ , whereas the compensating contribution from the shield is proportional to  $\omega^2$  in the numerator but is limited by the frequency-dependent denominator. As frequency rises, the inductive component  $j\omega L\epsilon$  increases the impedance of the “shield–ground” loop, thereby reducing the shield current. Consideration of capacitive couplings and distributed effects at the upper boundary of the frequency band ( $10 \text{ kHz}$ ) is deliberately omitted here and may be addressed in future studies, since in practical switching regimes of power systems and traction networks the dominant contribution to the induced EMF in the configuration under study comes from inductive coupling [6].

In multilayered soils, which are typical for industrial sites, the interpretation of Wenner and Schlumberger measurements is essential, involving the construction of a layered soil model to accurately predict the behavior of the grounding system in the kilohertz frequency range, where inductive effects further degrade performance. This layered modeling approach is necessary because apparent resistivity data from Wenner (equal probe spacing) or Schlumberger (variable current electrode separation) arrays reveal vertical variations in soil structure when plotted against probe spacing. At frequencies from several hundred Hz to tens of kHz, relevant to switching transients, harmonics, and high-frequency disturbances in power and traction systems, the inductive reactance of grounding conductors and paths becomes dominant. In multilayer soils, high-resistivity upper layers increase the effective impedance of current drainage paths, while deeper low-resistivity strata may not be fully utilized due to current confinement. Accurate layered models enable reliable prediction of frequency-dependent grounding impedance, step/touch voltages, and electromagnetic immunity of connected equipment, preventing underestimation of risks in transient conditions.

---

The dependence of grounding resistance on the length of electrode (Fig. 5) underscores that in industrial zones with moderate to high soil resistivity, relying on a single vertical electrode is generally insufficient to meet stringent low-impedance requirements ( $\leq 30 \Omega$ ) needed for reliable high-frequency compensation of induced voltages in shielded power cables. Therefore, practical implementations typically necessitate multiple parallel rods, extended horizontal conductors or grids, deep wells reaching lower-resistivity layers, or the application of conductive backfill materials. Future research will focus on investigating the optimal configuration of grounding electrodes (earthing arrangements) for soils characterized by low electrical conductivity (high resistivity, typically  $\rho > 0.5\text{--}40 \text{ k}\Omega\cdot\text{m}$ ), which are common in many industrial zones with dry sandy, rocky, made-ground, or seasonally frozen substrates.

The obtained dependencies provide a clear explanation for effects that are consistently observed in real-world operation. First, a distinct threshold in grounding resistance  $R_{\text{ground}}$  of approximately  $4\text{--}10 \Omega$  has been identified, beyond which even a minor increase in spreading resistance and/or deterioration of metallic bonding leads to an avalanche-like rise in induced voltage to hazardous levels. This finding correlates with the well-documented seasonal increase in CNC electronics failures during periods of drought and freezing, when soil resistivity and transition resistances of jumpers rise significantly, despite formally compliant values measured at 50 Hz [13]. Second, the frequency dependence elucidates why conventional overcurrent protective devices fail to prevent damage to microcontrollers, power switches, and input circuits: circuit breakers and fuses do not limit the amplitude or rate of rise of fast overvoltages and transient processes. The resulting engineering implication is the necessity to implement staged surge protective devices with minimal connection lengths and low-inductance discharge paths to the PE busbar, thereby reducing the  $|j\omega L|$  term in the kilohertz range [15]. Third, even when clearance zones around outdoor switchgear and overhead lines, as well as minimum distances from catenary systems, are observed, long power and signal cable routes connected to equipment remain exposed to electromagnetic induction as open inductive loops. In such cases, rational cable routing, additional shielding, transition to fiber-optic interfaces for control signals, and galvanic isolation enable a reduction in loop area and, consequently, in the primary induced EMF [19, 20].

Comparison of the present results with industry-specific guidelines for the protection of communication lines near railway catenary systems confirms that significant induced voltages can occur at distances of tens of meters from the source. In industrial shop-floor conditions, this corresponds to parallel power supply routes and cable trays running alongside main power feeders and transformers. This explains why localized mitigation measures applied only at the switchboard or machine level prove insufficient without a comprehensive solution encompassing the entire cable route and grounding system architecture.

## 5 Conclusion

This study developed a quantitative model describing the induced voltage in power supply lines of industrial equipment as a function of cable screen (PE conductor) grounding resistance and the frequency of the disturbing source in the 50 Hz – 10 kHz range. The derived analytical expression, based on a quasi-stationary three-conductor model with dominant inductive coupling, clearly reveals a pronounced threshold behavior: a sharp (avalanche-like) rise in induced voltage magnitude occurs when grounding resistance exceeds the narrow interval. Beyond this critical range the curve rapidly saturates, approaching the levels characteristic of an effectively ungrounded (open) screen condition.

These findings provide a physically consistent explanation for field phenomena: seasonal spikes in CNC electronics failures during dry summers and severe winters (when soil resistivity and contact resistances rise dramatically), systematic damage to input circuits, microcontrollers and power switches despite presence of conventional overcurrent protection, and insufficient performance of localized mitigation measures when long parallel cable routes remain exposed to power-frequency and harmonic magnetic fields.

The central practical implication is that grounding impedance must be treated as a strongly frequency-dependent parameter rather than a single 50 Hz value. Achieving and most importantly maintaining low impedance across the entire relevant spectrum becomes a key requirement for electromagnetic immunity of modern industrial automation.

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In typical industrial site conditions, where soil resistivity frequently lies in the 500-40000  $\Omega \cdot m$  range (and higher in made-ground or rocky areas), single vertical electrodes almost never suffice. Reliable performance demands extended configurations: multiple rods, horizontal conductors, meshed grids, deep wells reaching lower-resistivity strata, and/or application of ground enhancement materials (conductive backfill, bentonite mixtures).

The obtained results strongly support a systemic rather than local approach to EMC assurance: rational cable routing, consistent use of shielded lines, periodic verification of screen grounding quality, staged surge protection with minimized inductance, transition to fiber-optic interfaces where feasible, and, crucially, design of grounding and equipotential bonding systems with explicit consideration of the actual disturbance spectrum.

Future work will concentrate on optimization of grounding electrode configurations specifically for high-resistivity soils, incorporation of distributed line parameters at higher frequencies (tens of kHz), detailed numerical simulation of realistic multilayer profiles, and field validation on industrial test setups.

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# COMPARATIVE BOT DETECTION: RANDOM FOREST VERSUS XGBOOST IN SOCIAL NETWORKS

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## ABSTRACT

**Relevance and Objective:** This study investigates the detection of automated accounts (bots) on social networks by comparing the behavior and performance of Random Forest and XGBoost classifiers under realistic, minimally tuned conditions. **Materials and Method:** A dedicated Twitter dataset was compiled, including human-operated and automated accounts with profile-level, activity, and network-based metadata. Pre-processing involved median and mode imputation for missing values and normalization of numeric features, without feature selection or dimensionality reduction, allowing the models to internally determine feature importance. Both classifiers were trained on stratified splits, and performance was evaluated using accuracy, precision, recall, and F1-score, while misclassified accounts were qualitatively analysed to understand patterns causing ambiguity. **Results:** Results indicate that both models achieve near-chance performance, with Random Forest slightly outperforming XGBoost, demonstrating higher accuracy and balanced recall across classes. Many misclassified accounts exhibited intermediate activity, irregular posting, and follower-to-following ratios, highlighting intrinsic ambiguity that metadata and activity-based features alone cannot resolve. **Conclusions:** These findings demonstrate that algorithmic sophistication alone is insufficient to overcome weak or noisy signals in real-world social network data. Limitations include the dataset not covering all possible bot behaviors, exclusion of textual content, and minimal hyperparameter tuning, which may affect generalizability. Practically, the study underscores the importance of enhanced feature design, hybrid modeling approaches, and adaptive learning strategies for improving bot detection. By providing a transparent comparison under realistic conditions, this work reveals the challenges of automated account detection and offers insights for both research and practical applications in social media analysis.

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**KEYWORDS:** *Social bots, Random Forest, XGBoost, feature analysis, classification challenges.*

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## 1 Introduction

Social networking platforms have steadily moved from being informal communication tools to becoming spaces where opinions, narratives, and visibility are shaped in subtle ways. Much of this activity is driven by real users, but automated accounts are now an established part of these environments. Some automation is expected and even encouraged by platforms themselves. At the same time, there is a growing number of accounts whose purpose is less transparent, particularly those aimed at amplifying content or influencing engagement patterns. This has made it harder to separate organic activity from coordinated or automated behavior.

The issue is not simply that bots exist, but that their behavior no longer looks obviously artificial. Earlier studies often relied on clear signals such as posting frequency or repetitive text, and these approaches were effective at the time. In more recent datasets, however, such signals appear far less reliable. Many automated accounts now exhibit behavior that closely resembles that of low-activity or irregular human users. In some cases, even manual inspection does not lead to confident classification. This overlap is one of the reasons why bot detection remains an open problem rather than a settled one.

Because of these changes, detection strategies based on fixed rules have gradually become less useful. This is a point that appears repeatedly in the literature, but it is also evident when working directly with social network data. Features that seem informative in one dataset often lose relevance in another, especially when data is collected from different time periods or platforms. As a result, learning-based methods are frequently adopted, not because they are perfect, but because they can adapt more easily to variation and noise.

Ensemble learning approaches are often part of this shift, although the choice of a specific method is not always well justified. Random Forest is commonly used, in part because it behaves in a stable manner and tends not to overreact to individual features. XGBoost is also popular, particularly when higher performance is expected, though its behavior can vary depending on how the data is structured. Both methods have been applied to bot detection tasks, sometimes on similar datasets, but direct comparisons are not always the main focus.

In practice, the differences between such models become noticeable when dealing with real social network data. Datasets are often imbalanced, labels may be noisy, and feature distributions can shift over time. During preliminary experiments for this work, it was observed that small changes in feature selection or sampling affected the models differently. These observations were not always reflected in overall accuracy scores, but they influenced consistency and error patterns. Such effects are easy to overlook when results are reported in aggregate.

This study therefore looks at bot detection through a comparative analysis of Random Forest and XGBoost, using the same dataset and feature space. The goal is not to identify a universally superior method, but to examine how each approach responds to the characteristics of social network data. By focusing on their behavior as well as their performance, the paper aims to provide insight that is relevant for both experimental research and applied detection systems.

## 2 Related Work

Work on automated accounts in social networks did not begin with detection algorithms. Early studies were mostly concerned with identifying whether automation existed and what role it played in online communication. Cresci [1] provided one of the most influential early discussions, framing social bots as actors capable of shaping information flow rather than isolated technical anomalies. This framing influenced later work by emphasizing impact over purely technical classification.

Some of the first detection-oriented studies relied on behavioral regularities. Wang et al. [2] analysed Twitter accounts and showed that automation could be inferred from activity patterns and interaction behavior. A notable outcome of their work was the observation that many accounts combine human and automated actions, rather than fitting neatly into a single category. This idea later reappeared in multiple studies and complicated the assumption of binary classification.

As platforms and automation strategies evolved, earlier heuristics became less reliable. Cresci [1] demonstrated that newer generations of spambots were explicitly designed to evade detection by imitating human behavior. Their findings suggested that static rules were unlikely to remain effective over time. Similar concerns were raised by

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Zhang et al. [4], who showed that even when multiple feature types were combined, certain accounts remained difficult to classify with confidence.

Machine learning approaches became more common as datasets grew in size and complexity. Random Forest classifiers were widely adopted during this phase, often because they handled heterogeneous features without extensive pre-processing. Gomez and Martinez [5] used ensemble learning to infer latent attributes in social networks, while Müller and Schmidt [6] applied similar techniques to spam detection. In both cases, Random Forest models were valued more for robustness than for optimal accuracy.

Boosting-based methods gained attention somewhat later. Gradient boosting models, including XGBoost, were applied to bot detection with the expectation of capturing more complex patterns. Zhao et al. [7] reported performance improvements using boosting techniques, though they also noted sensitivity to data sampling and feature construction. Comparative work by Kim et al. [8] suggested that differences between ensemble classifiers were often smaller than expected, especially when strong feature sets were used.

Several review-style and longitudinal studies emphasized that bot detection is not a static problem. Cresci [1] argued that detection methods must account for behavioral evolution, while results from the DARPA Twitter Bot Challenge [9] showed that models trained on one dataset often failed when exposed to new bot strategies. These findings highlighted the limits of evaluation based on a single benchmark.

More recent studies explored neural and hybrid approaches. Li et al. [10] proposed deep learning models for bot detection, and Zhang et al. [11] applied graph neural networks to capture relational information. While these methods demonstrated promising results, they often required large labeled datasets and significant computational resources, which limited their applicability in some settings.

Concerns about dataset bias and temporal validity have also been raised. Cresci [1] showed that bot behavior changes over time, reducing the usefulness of static labeled datasets. Nguyen and Vo [13] further noted that human behavior itself is highly variable, which makes strict separation difficult. Tools such as BotOrNot [29] and studies on coordinated automation [15] demonstrated that detection accuracy can vary significantly depending on context.

Other work examined manipulation and abuse in specific domains. Ivanov [16] focused on political abuse in social media, while Rossi et al. [17] proposed unsupervised techniques for detecting coordinated behavior. Research on political communication [18], fake account detection [19], and temporal activity patterns [20] further illustrated the diversity of approaches and assumptions present in the literature. Studies linking bots to misinformation diffusion [21] reinforced the broader societal relevance of detection research.

Taken together, existing studies show that bot detection remains an evolving and context-dependent problem. While Random Forest and XGBoost are both widely used, their selection is often guided by reported accuracy rather than careful examination under identical conditions. This gap motivates the present work, which compares these two methods using the same dataset and feature space, with attention to differences that may not be evident from aggregate metrics alone.

### **3 Methodology**

This study investigates the detection of automated accounts in social networks using Random Forest [22] and XGBoost [23] classifiers. The primary aim is to evaluate how each model performs under comparable conditions rather than pursuing exhaustive hyperparameter optimization. The methodology emphasizes transparency in feature handling, pre-processing, and evaluation, ensuring that the results can be reproduced or extended in future work [24].

#### **3.1 Dataset**

For this research, a Twitter Bot Detection dataset was compiled specifically for experimentation. The dataset includes accounts labeled as either human-operated or automated (bot). Data collection involved aggregating account metadata, activity logs, and network interaction statistics over several months. Labels were assigned through a

combination of automated heuristics and manual verification. While it may not encompass all possible bot behaviors, the dataset is representative of typical patterns observed in social media.

The dataset contains multiple types of features. Profile-level attributes include account age, profile description length, and verification status. Activity features comprise tweet frequency, retweet and mention ratios, and temporal posting patterns. Network-based features include followers-to-following ratios and engagement metrics. During preliminary analysis, it was observed that human accounts significantly outnumber bot accounts. This imbalance was intentionally retained to reflect realistic conditions on social networks. It also presents an additional classification challenge, reflecting real-world scenarios in which bots are relatively rare.

Some numeric features contained missing values, and several categorical attributes required normalization or encoding. Occasional extreme values were also observed in activity metrics. These values were not removed to preserve the dataset's integrity, acknowledging that real-world data often contains noise. Overall, creating and reviewing this dataset helped identify subtle patterns in account behavior, which informed later pre-processing and modeling choices.

### 3.2 Pre-processing and Feature Handling

Pre-processing involved filling missing numeric values using median imputation and categorical values using the mode [14]. Numeric features with widely varying ranges were normalized [1]. No dimensionality reduction or manual feature selection was applied, allowing the models to internally determine feature importance [9]. This approach tests the robustness of each model and reveals how they handle potentially redundant or correlated features [3]. During data review, certain features appeared strongly correlated with bot behavior; however, over-engineering was avoided to maintain an unbiased analysis [5].

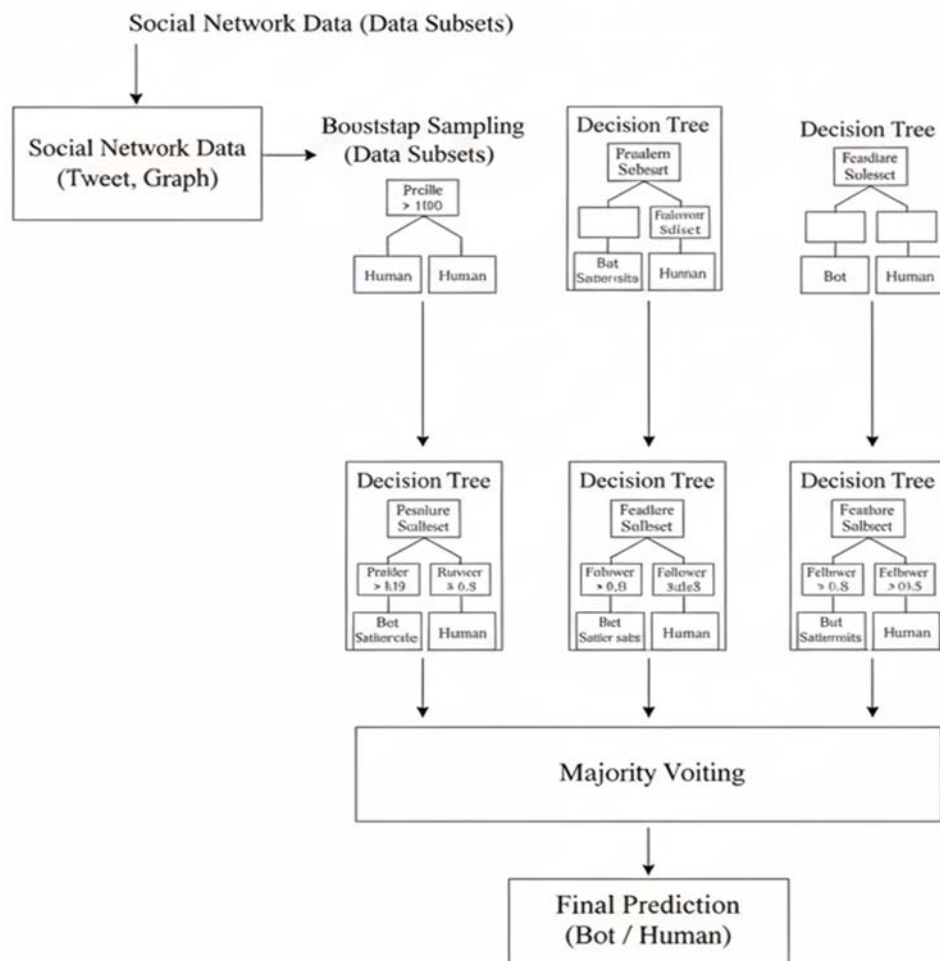


Figure 1. Random Forest Architecture for Bot Detection

Textual content from tweets was excluded to reduce overfitting and platform-specific bias [2]. While including text features might improve predictive accuracy, it would also introduce additional noise from language variation and topic differences. Focusing on metadata and activity features allows the models' results to generalize better across users and time periods [12].

### 3.3 Model Construction

Two ensemble learning algorithms were implemented: Random Forest [22] and XGBoost [23]. The Random Forest model consisted of multiple decision trees trained on random subsets of data and features [8].

The number of trees was determined through preliminary testing, balancing stability and computation time. XGBoost, implemented as a gradient boosting framework, builds trees sequentially to correct residual errors from previous iterations.

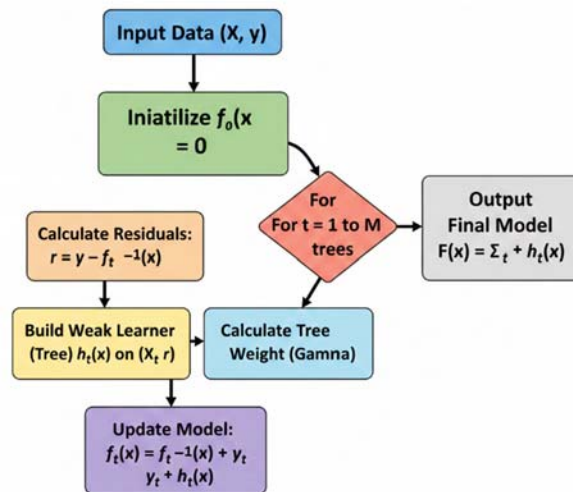


Figure 2. Flow Chart of XGBoost

Regularization parameters were applied to reduce overfitting [19]. Hyperparameter tuning was intentionally minimal to allow a fair comparison between the models without introducing bias.

### 3.4 Experimental Setup

The dataset was divided into training and testing sets using stratified sampling to preserve class distributions [24]. Performance metrics included accuracy, precision, recall, and F1-score, providing a more comprehensive assessment than accuracy alone, particularly given the class imbalance [22,24]. Beyond aggregate metrics, misclassified accounts were examined qualitatively to understand model behavior in borderline cases [5]. Certain accounts were consistently misclassified by both models, highlighting the challenge of distinguishing sophisticated bots from human-operated accounts [12].

Experiments were repeated across multiple random seeds to reduce variability caused by random data splits [9]. Minor differences were observed across runs; however, overall trends remained consistent, supporting the reliability of the findings [3].

## 4 Results

This section presents the experimental results obtained using the Random Forest and XGBoost classifiers under the conditions described in the previous section. The results are reported using standard classification metrics, including accuracy, precision, recall, and F1-score. Given the balanced test set and the retained class imbalance during training, these metrics allow for a more nuanced interpretation than accuracy alone.

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#### **4.1 Random Forest Performance**

The Random Forest classifier achieved an overall accuracy of 0.5073 on the test set. At first glance, this value appears close to random guessing; however, a closer inspection of class-wise performance reveals more detail about the model's behavior. For class 0 (human-operated accounts), the model achieved a precision of 0.51 and a recall of 0.53, resulting in an F1-score of 0.52. This indicates that the model was slightly more effective at identifying human accounts than bot accounts.

For class 1 (automated accounts), precision was 0.50 and recall was 0.49, with an F1-score of 0.50. The lower recall for bot accounts suggests that a substantial number of automated accounts were misclassified as human-operated. This asymmetry is notable, as it reflects the difficulty of distinguishing bots that intentionally mimic human-like behavior using metadata and activity features alone.

The macro-averaged precision, recall, and F1-score were all approximately 0.51, indicating relatively uniform performance across classes. The weighted averages were similar, which is consistent with the near-balanced class distribution in the test set. While the Random Forest model did not demonstrate strong predictive power, its behavior was relatively stable across repeated runs, with limited variance in the reported metrics. This stability suggests that the model consistently struggled with the same types of borderline cases rather than producing erratic classifications.

#### **4.2 XGBoost Performance**

The XGBoost classifier achieved a slightly lower overall accuracy of 0.4991, though the difference compared to Random Forest is marginal. Class-wise analysis shows that for class 0, precision was 0.50, recall was 0.41, and the F1-score was 0.45. For class 1, precision reached 0.50, recall increased to 0.59, and the F1-score increased to 0.54. In contrast to Random Forest, XGBoost demonstrated a more pronounced imbalance in its treatment of classes. While Random Forest maintained recall values relatively close to parity (0.53 and 0.49), XGBoost showed a significant gap, with a recall of 0.41 for humans and 0.59 for bots.

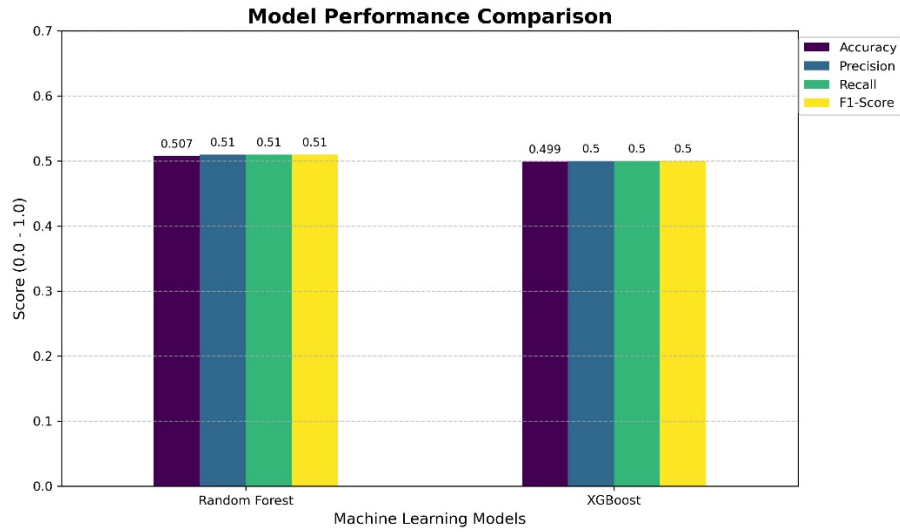
The macro-averaged and weighted metrics for XGBoost were all approximately 0.50, reflecting a symmetrical performance across human and automated accounts. While this balance may appear desirable, it also suggests that the model did not strongly favor discriminative features for either class. In practical terms, XGBoost appears to distribute its errors more evenly rather than concentrating misclassifications in one class.

During repeated experiments with different random seeds, Random Forest showed slightly greater variability in individual predictions compared to XGBoost, although aggregate metrics remained consistent. This observation aligns with the inherent randomness in the ensemble construction of Random Forest, where variations in bootstrap samples and feature selection can cause fluctuations in predictions. However, this variability did not translate into substantial performance gains under the present experimental conditions.

#### **4.3 Comparative Observations**

When comparing the two models directly, neither Random Forest nor XGBoost demonstrates clear superiority in terms of overall accuracy or F1-score. Random Forest demonstrated more balanced recall across both classes (0.53 and 0.49), whereas XGBoost showed a higher sensitivity toward automated accounts at the expense of human-operated account recall (0.41 vs 0.59). These differences are subtle and are not fully captured by accuracy values alone.

An examination of misclassified instances revealed that many accounts were consistently misclassified by both models. These accounts often exhibited moderate activity levels, irregular posting patterns, and follower-to-following ratios that did not strongly indicate either human or automated behavior. Such cases highlight the limitations of relying solely on metadata and activity-based features for bot detection, particularly when bots are designed to blend into typical user populations.



**Figure 3.** Comparison of Result

Table 1

Performance Metrics Comparison for Bot Detection

Model	Accuracy	Precision	Recall	F1-Score
Random Forest	0.5073	0.51	0.51	0.51
XGBoost	0.4991	0.50	0.50	0.50

The following features were identified as the primary drivers for classification in both models (Table 2).

Table 2

Top 5 Feature Importance (Relative Contribution)

Rank	Feature	Description
1	Follower/Following Ratio	Disparity between account reach and social ties
2	Status Count	Total volume of posted content
3	Account Age	Duration since account creation
4	Favourites Count	Level of interaction with other users' content
5	Entropy of posting	Regularity and timing of activity patterns

Overall, the results suggest that under identical feature representations and minimal tuning, both ensemble methods face similar challenges. The relatively low performance does not necessarily indicate model failure but instead reflects the inherent difficulty of the task and the ambiguity present in the dataset. These findings reinforce the argument that improvements in bot detection may depend as much on feature design and data quality as on the choice of classification algorithm.

## 5 Discussion

The results reported in the previous section may near-chance accuracy (0.5073) highlights the failure of metadata-only features in realistic settings, particularly when viewed through the lens of accuracy-centered evaluation. Both Random Forest and XGBoost achieved performance close to chance level, which contrasts with a number of

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published studies that report substantially higher scores for bot detection tasks. However, this contrast is precisely what makes the present findings meaningful rather than dismissible.

A recurring pattern in prior work is the use of highly curated datasets or feature sets that implicitly encode strong assumptions about bot behavior. For example, studies such as those by Zhang et al. [4] and Zhao et al. [7] report classification accuracies exceeding 0.80, but these results are typically obtained under controlled conditions where features are carefully selected and often include content-based or temporal regularities that may not persist over time. In comparison, the present study deliberately avoids aggressive feature engineering and excludes textual content, which reduces overfitting but also exposes the limits of metadata-driven detection.

This difference in methodological emphasis helps explain the performance gap. While Random Forest and XGBoost are both capable of capturing non-linear patterns, they cannot compensate for weak or ambiguous signals in the input data. Cresci [1] previously noted that modern bots are increasingly designed to blend into normal user populations, making them difficult to detect using traditional activity-based features. The results observed here align closely with that argument. The models do not fail randomly; rather, they consistently struggle with the same accounts, particularly those that occupy a behavioral middle ground between clear automation and typical human usage.

Several recent studies have explored more complex models in response to this challenge. Deep learning approaches, such as those proposed by Li et al. [10], report improved detection performance by leveraging large-scale representations and content embeddings. Similarly, graph-based methods introduced by Feng et al. [25] attempt to capture relational structure that is invisible to node-level features alone. While these approaches show promise, they also introduce new constraints, including higher computational cost, reduced interpretability, and reliance on large labeled datasets that are difficult to maintain over time.

In this context, the present study serves a different purpose. Rather than demonstrating maximal performance, it highlights the practical limitations of widely used ensemble classifiers when applied under realistic and minimally tuned conditions. This perspective is often missing from the literature, where negative or neutral results are underreported. As noted by Lipton[26], overly optimistic benchmarks can create misleading expectations about model effectiveness in real-world deployments. The near-chance performance observed here suggests that, without stronger features or adaptive labeling strategies, even well-established classifiers may offer limited benefit.

The comparison between Random Forest and XGBoost further reinforces this point. While XGBoost is frequently assumed to outperform Random Forest due to its boosting mechanism, the results here do not support a strong advantage. Similar observations were reported by Lee [27], who found that boosting methods do not consistently outperform bagging-based ensembles when feature quality is the dominant limiting factor. In this study, XGBoost's more balanced recall across classes did not translate into meaningful gains, indicating that model sophistication alone is insufficient.

Another important implication relates to evaluation practices. Many prior studies emphasize accuracy or F1-score as primary indicators of success. However, as demonstrated here, aggregate metrics can obscure systematic weaknesses. Accounts misclassified by both models were not outliers in a statistical sense; instead, they reflected realistic user behavior that challenges binary labeling. This observation echoes findings by Gilani et al. [28], who argued that human behavior itself is highly variable and often overlaps with automated patterns, particularly for low-engagement users.

Taken together, these observations help clarify why this paper is necessary despite its modest numerical results. The contribution lies not in outperforming existing methods, but in exposing the fragility of common assumptions under realistic conditions. By applying Random Forest and XGBoost to the same dataset, with the same features and minimal tuning, the study isolates model behavior from dataset-specific optimizations. This approach provides insight into what these classifiers can—and cannot—be expected to do in practical settings.

Finally, the findings suggest that future progress in bot detection may depend less on incremental algorithmic improvements and more on rethinking feature representations, labeling strategies, and evaluation protocols. Hybrid approaches that combine metadata with adaptive temporal or relational features may offer a way forward, but such methods must be tested with the same level of restraint applied here. Without this, reported improvements risk being confined to benchmark datasets rather than translating into robust, deployable systems.

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## 6 Limitations

While the study provides some insight into the behavior of Random Forest and XGBoost classifiers on social network bot detection, several limitations are apparent and worth discussing. First, the dataset, although compiled specifically for this research, cannot capture all possible account behaviors. Despite careful attempts to include a variety of account types, it is likely that certain sophisticated bots or less common behavioral patterns were not represented. This means that model performance observed here may not generalize perfectly to other social networks, or to bots that evolve new strategies over time. One has to keep in mind that social media behavior is dynamic, and what is captured in a few months might not reflect future patterns.

Second, the study intentionally avoided extensive hyperparameter tuning or heavy feature engineering. This allowed for a fair comparison between the two models under identical conditions, but it may have limited their predictive potential. It is plausible that, with more targeted optimization or carefully engineered features, both Random Forest and XGBoost could have achieved higher accuracy. Nevertheless, that was not the aim here; the purpose was to observe their raw behavior under minimal assumptions.

Third, textual content from tweets was excluded. While this choice helps reduce overfitting and avoids platform-specific bias, it also limits the ability to capture behavioral nuances expressed in content. Integrating text or semantic features could potentially improve classification, as noted in previous studies, but doing so also increases complexity and may introduce language- or topic-specific biases that are difficult to control.

Another limitation concerns the temporal range of the collected data. Although accounts were observed over several months, social media activity evolves rapidly, and patterns seen in this dataset may not persist indefinitely. Similarly, human behavior itself is inherently variable, sometimes overlapping with bot-like activity, which creates ambiguity and complicates classification. This overlap is difficult to account for using purely metadata-driven approaches.

Finally, the study does not explore operational constraints such as real-time detection, scalability, or adaptive learning. These are important considerations for practical deployment, but they fall outside the scope of the current experimental setup. Taken together, these limitations indicate that the study should be considered exploratory and descriptive. It aims to shed light on the behavior of commonly used classifiers, rather than to establish the ultimate benchmark in bot detection.

## 7 Conclusion

This study examined the detection of automated accounts on social networks using Random Forest and XGBoost classifiers under controlled, minimally tuned conditions. By compiling a dedicated dataset and limiting hyperparameter tuning, the research sought to reveal the inherent behavior of these classifiers, rather than achieving maximum accuracy.

The results indicate that both classifiers struggle to reliably separate human-operated accounts from bots using only profile-level, activity, and network-based metadata. Random Forest showed slightly higher recall for human accounts, whereas XGBoost achieved a more balanced treatment of both classes. Still, neither classifier surpassed chance-level performance in a meaningful way, and a large proportion of misclassified accounts were shared between models. This pattern suggests that certain accounts present intrinsic ambiguity, which cannot be easily resolved with standard ensemble methods.

Comparison with previous studies demonstrates that higher reported accuracies often rely on curated datasets, additional feature types, or deep content analysis. In contrast, the present study emphasizes realistic conditions, minimal tuning, and raw feature sets. As such, the modest performance is not a failure but an important indicator of the challenges posed by real-world social network data. It highlights the difficulty of detecting subtle automated behaviors that closely mimic human patterns.

Despite these limitations, this work contributes meaningfully to the literature. It provides a transparent and cautious examination of ensemble classifiers, illustrating where and why they struggle. The findings underscore that future progress in bot detection may rely more on improved feature design, hybrid methods combining multiple modalities, or adaptive learning strategies, rather than incremental algorithmic changes alone.

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In summary, the study offers a candid account of classifier performance, emphasizes methodological transparency, and provides guidance for future research. By focusing on realistic experimental conditions and examining classifier behavior carefully, it adds practical insight to ongoing efforts in automated social media analysis.

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# ASSESSING THE POSSIBILITIES OF IMPROVING COMMUNICATION QUALITY IN MODERN CORPORATE COMMUNICATION NETWORKS

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## ABSTRACT

The object of this study is an access node based on IP-PBX (Internet Protocol Private Branch Exchange) technology as part of a fixed network infrastructure. Unified communications is being implemented, facilitating comprehensive communication and collaboration. Specifically, it integrates voice, video, instant messaging, presence information, email, and document management onto a single platform. Companies across various sectors are investing in IP-PBXs to improve operational efficiency. IP-PBX telecommunications systems deliver voice and multimedia services over an Internet Protocol data network. They replace traditional circuit-switched and time-division multiplexing (TDM) PBX systems by using packet-switched networks and converging voice and data communications into a single infrastructure. This convergence offers significant advantages in terms of cost, scalability, management, and feature integration. Subject of the research: algorithms for distributing node bandwidth between serviced information flows. IP PBXs in corporate communications networks provide communications over existing data networks. Beyond simple cost savings, these systems lay the foundation for the development of unified communications (UC), which integrate disparate communication tools for services such as voice, video conferencing, instant messaging, and email into a single platform. This article presents an approach to studying the operation of a fixed-line node in the context of the transition to unified IP solutions. Various options for the combined transmission of traffic types such as voice and document flow files are discussed. A mechanism for priority resource allocation with a spillover effect is proposed. In this case, voice messages rejected in the main resource segment can be redirected (spilled) to an additional segment used together with file traffic. This approach reduces the overall probability of voice call loss. The negative impact of document flow will affect a small portion of voice traffic. The complex dynamics of flow interactions requires in-depth mathematical analysis.

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**KEYWORDS:** *Internet Protocol; Private Branch Exchange; Complete Sharing; Overflow; Network Slicing.*

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## 1 Introduction

The object of this study is an access node based on IP-PBX (Internet Protocol Private Branch Exchange) technology as part of a fixed network infrastructure.

The global IP-PBX market is demonstrating robust growth. The broader "call management" market, which includes traditional and IP-PBX systems, was valued at \$18.88 billion in 2023. It is projected to reach \$48.11 billion by 2032, growing at a compound annual growth rate (CAGR) of 10.77%. Within this market, the IP extensions segment is considered the fastest-growing category. This growth is driven by increasing demand for cost-effective, flexible, and high-quality communications solutions, the widespread adoption of 5G technology, and the widespread bring-your-own-device (BYOD) trend.

Unified communications (UC) is being implemented, facilitating comprehensive communication and collaboration. Specifically, it integrates voice, video, instant messaging, presence information, email, and document management onto a single platform.

Companies across various sectors, particularly banking, financial services, retail, e-commerce, and hospitality, are investing in IP-PBXs to improve operational efficiency. IP-PBX telecommunications systems deliver voice and multimedia services over an Internet Protocol (IP) data network. They replace traditional circuit-switched and time-division multiplexing (TDM) PBX systems by using packet-switched networks and converging voice and data communications into a single infrastructure.

This convergence offers significant advantages in terms of cost, scalability, management, and feature integration.

The core network is a critical component of the architecture, not simply a data link. Quality of Service (QoS) is essential for prioritizing voice traffic over data packets to minimize latency, jitter, and packet loss, which directly impact call quality. This is implemented using mechanisms such as DiffServ (differentiated services) on network switches and routers.

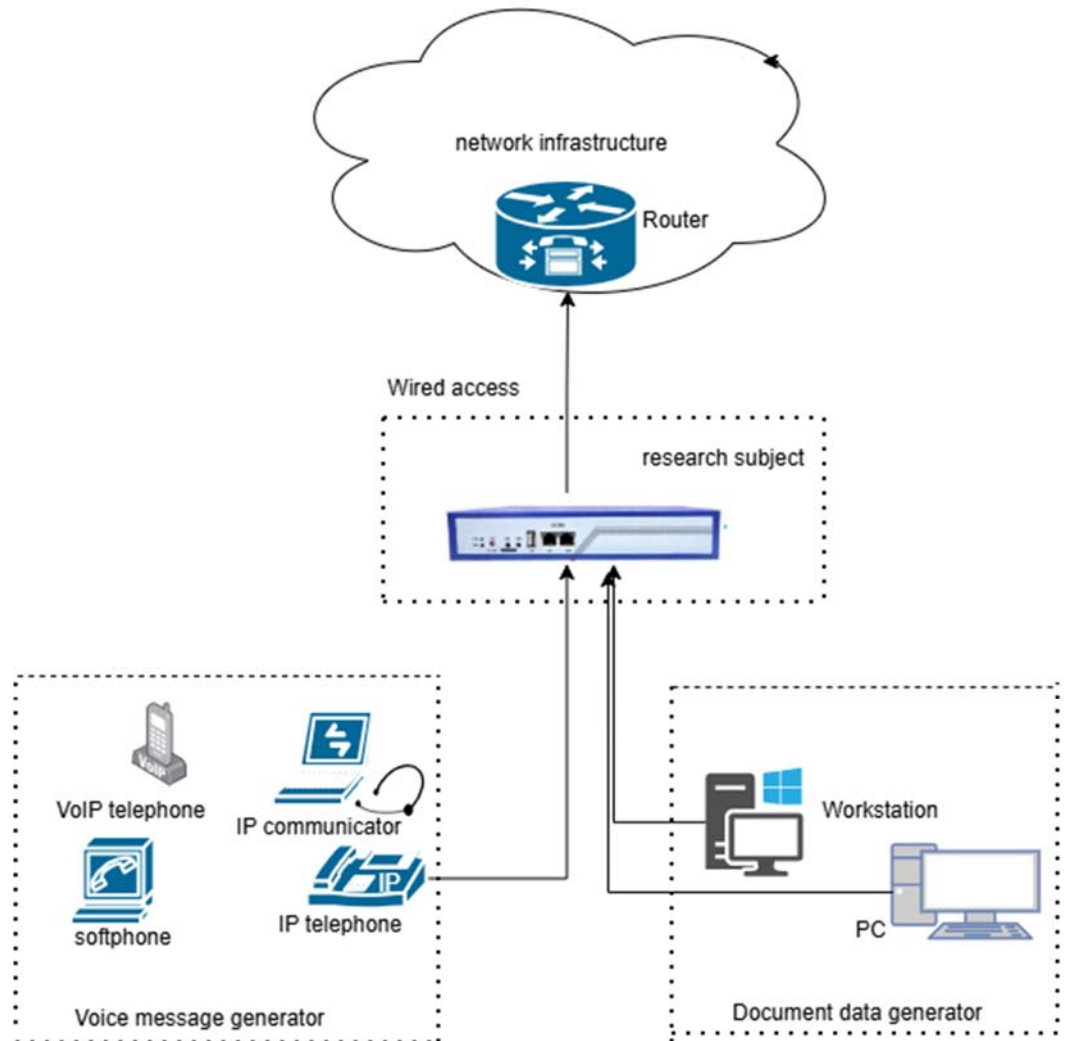
Traffic arriving at an IP PBX has a complex set of interrelated characteristics: heterogeneity – a combination of delay-sensitive voice and data traffic; randomness – flows are often modeled by Poisson processes; quality of service (QoS) requirements – voice communications require minimal delays and losses; limited access node bandwidth – efficient resource allocation between heterogeneous flows is essential [1-5].

Considering these characteristics is critical during design, for resource planning, and for ensuring guaranteed voice communication quality in the face of bandwidth competition. Otherwise, there is a risk of degraded voice connection quality, increased losses, and ineffective use of network resources, which directly impacts user satisfaction and the reliability of telecommunications services. Subject of the research: algorithms for distributing node bandwidth between serviced information flows.

## 2 Functional model of a fixed access node

A fixed access node based on IP-PBX is an integrated communication system, including a virtual PBX, a fixed access system, subscriber terminals and gateways for connecting to public networks (see Fig. 1). IP PBX performance is analyzed in terms of efficient processing and prioritization of mixed traffic (voice messages and files) under conditions of limited channel resources. IP PBX algorithms for resource allocation between priority voice messages and data files are studied.

IP-PBX (also known as IP-PBX) systems are based on unified software and standard multiservice platforms. IP-PBX systems transmit information over the public internet using IP-SEC (Internet Security) protocols or through specialized IP-MPLS (Multi Protocol Label Switching) networks.



**Figure 1.** Including a fixed access node in a packet network

IP PBXs are widely used in corporate communications networks. Among the most in-demand features are the following [2, 3, 6-9]:

- implementing a personalized approach to each client;
- discovering effective service promotion methods.

A characteristic of the development of the computer industry, which competes with traditional communications systems, is the desire to use universal approaches. A server of any brand can be used with equipment from other brands, and any operating system can be used, be it Windows, Linux, or macOS. An example is the popular multiservice platform Asterisk, which is open source. Asterisk is flexible software that can be installed on any Linux-based platform. Besides Asterisk, there are competing VoIP PBXs, such as Elastix and Askozia PBX.

The most commonly used codecs in digital communication networks are G.711, which convert speech into a digital data stream with a primary digital channel speed of 64 kbps. Low-speed codecs of various types are used directly in IP telephony networks. Recently, support for wideband voice codecs such as G.722 has become popular.

They provide HD Voice (High-Definition Voice), i.e. high-definition sound, operating at a speed of 48, 56, or 64 kbps. Thus, the G.722.1 codec provides operation at speeds of 24 and 32 kbps with a bandwidth of 50 Hz – 7 kHz. A frequently used variant of the G.722.2 codec, also known as Adaptive Multi Rate – WideBand (AMR-WB), offers the ability to quickly change the compression rate as the bandwidth of the data transmission network changes. G.722.2 defines nine different transmission rate modes, ranging from 6.6 kbps to 23.85 kbps. In Russia, it is used in cellular operator networks under the name HD Voice technology.

A commonly used approach to assessing the throughput of packet networks and their components (including in the access subsystem) is to estimate the required speed per unidirectional connection. This is based on the size of the transmitted packets and the packetization period, which in turn depend significantly on the codecs and network protocols used, which generate and attach so-called "overhead" costs to each information packet. We will determine the network layer throughput for a single voice connection using the formula:

$$B = 2 \times (Pt \times 8 / 1000) \times N, \tag{1}$$

where Pt (Payload) is the final packet size, taking into account overhead, in bytes:

$$Pt = RP + O, \tag{2}$$

where RP is the packetization size in bytes per packet, defined as  $RP = (T_{packet} / 1000) \times (\text{codec throughput} \times 1000 / 8)$ ; where  $T_{packet}$  is the packetization period; O is the overhead, in bytes; N is the number of packets per second.

The coefficient 2 reflects the two-way nature of the connection [2, 3].

The packet rate per second (PPS) can be calculated by taking the reciprocal of the packetization period. The required speed for a single one-way internet connection varies significantly between codecs and depends on the network technologies used (whether using IP-SEC or MPLS).

For example, a delay of up to 2 minutes in receiving an internal email is perfectly acceptable from a user perspective, but connection interruptions, distortion, or loss of sound or video can cause a negative reaction.

### 3 Factors affecting voice traffic transmission quality in packet-switched networks

For telecom operators, it's important to maximize network resource utilization while maintaining the expected transmission quality. This involves monitoring: packet delays; delay variations; and packet loss.

The universal criterion for comparing voice transmission quality across different technologies is the subjective assessment method recommended by the International Telecommunication Union (ITU-T) [2, 7, 8, 10-12].

The assessment is performed using Quality Rating (R) on a 100-point scale or Mean Opinion Score (MOS) on a 5-point scale (see Table 1).

Table 1

Speech quality assessment according to ITU-T Recommendation G.109 (09/99)

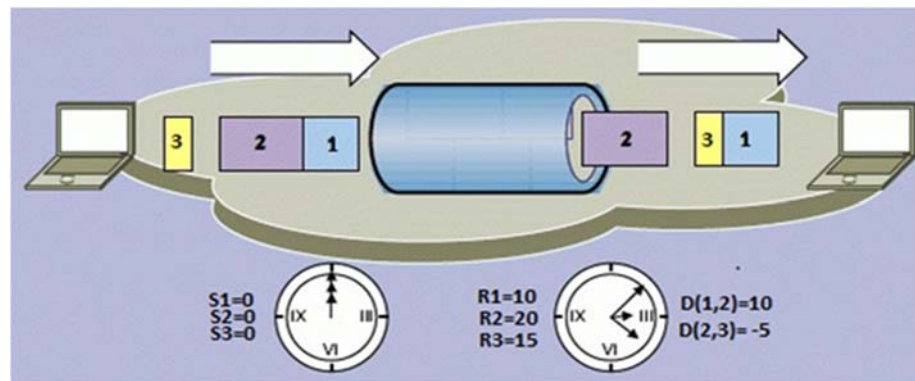
Range R	Speech quality category MOS score	
90 < R < 100	best	4.34 – 4.5
80 < R < 90	high	4.03 – 4.34
70 < R < 80	medium	3.60 – 4.03
60 < R < 70	low	3.10 – 3.60
50 < R < 60	poor	2.58 – 3.10

MOS units are related to R by a complex nonlinear dependence (Rec. G.107). The highest quality R = 100 corresponds to MOS = 4.5. In practice, for a quick recalculation in the most important range  $2.5 < \text{MOS} < 4.4$ , a linear approximation of the form  $\text{MOS} = R / 20$  is convenient. Its error is less than 5%, which is quite acceptable, taking into account the spread in subjective assessment. Connections with  $\text{MOS} < 2.5$  are not recommended. Moreover, for good quality connections, it is desirable to limit yourself to the first three speech quality categories from Table 1, that is, to ensure  $R > 70$ , or  $\text{MOS} > 3.5$ . ITU has developed a recommendation on the issue of standardizing quality of service in IP networks Y.1541 "Network Performance objectives for IP-based services". It defines QoS (quality of service) classes for each data flow between the user and the Internet access provider.

Quality of service standards are defined for the entire end-to-end section of the IP network architecture model (IP network Cloud). IP networks define six classes of service (from 0 to 5). Each class corresponds to specific IP network applications. Upper bounds for the following parameters are defined for each class of service: IPTD – IP packet transmission delay; IPDV – IP packet delay variation; IPLR – IP packet loss ratio; IPER – IP packet error rate.

IP-based networks not only deliver data but also serve as transport for a wide variety of services with varying network requirements. From the perspective of an IP network transporting network services, the quality of the transport environment is determined by several parameters:

- connection speed to the backbone network;
- IP packet loss (loss rate, or packet loss);
- round-trip delay (RTD; round-trip time RTT; round-trip latency, RTL);
- jitter (IP packet delay variation, or IPDV; packet delay variation, or PDV). As an example, consider jitter, which is defined in RFC 3393 as the difference in the end-to-end delays of two packets (Fig. 2).



**Figure 2.** Delay Variation Due to Packet Delivery Variation

If R is the packet's sending time and S is its delivery time, then the PDV value for packets with numbers i and j is calculated as follows:

$$D_{i,j} = (R_j - R_i) - (S_j - S_i) = (R_j - S_j) - (R_i - S_i).$$

RFC 3550 defines a method for calculating the variance for a series of packets:

$$J_i = J_{i-1} + (|D_{i-1,i}| - J_{i-1})/16.$$

The measurement uses average PDV values over a given time period. Delay variations arise from the very nature of packet switching in an IP network. Ideally, the variation is zero, meaning packet delivery times are uniform.

However, due to the non-uniformity of the network flow passing through network nodes, as well as the operation of differentiated service mechanisms for network traffic, variations are not zero. It should be noted that the voice and data transmission quality indicators listed above characterize and normalize only a portion of the characteristics of packet traffic transmission.

#### 4 Features of joint transmission of speech and document files

At the IP-PBX access point in a packet network, the connection speed is typically limited and is selected based on the cost of resource rental. When transmitting voice packets and document files simultaneously, an extremely unpleasant phenomenon occurs: voice packet transmission stops while the file is being downloaded. All active subscribers experience lengthy connection interruptions. This factor is not taken into account in ITU-T recommendations. But its negative impact is felt by users. There are several options for protecting against this phenomenon: transmitting data traffic in fragments, minimizing the mutual influence of different types of traffic using the Network Slicing approach.

Tables 2 and 3 present the calculated voice connection interruptions during document file transfers. Thus, the larger the file being transferred, the longer the connection interruption will last. Similarly, the greater the available bandwidth, the faster the file will be transferred. File transfer essentially consumes all available bandwidth for a certain period of time. Voice call packets can wait for transmission for a limited time. After this time, they are replaced by new ones, which may also be transmitted or lost.

Table 2

Calculated voice connection interruption duration in M/G/1 QSO for a 1 MB file size

Document file fragment size, MB			
1.0	0.5	0.2	0.1
Voice connection interruption duration per TF seconds during document file transfer in fragments			
2.67	1.34	0.534	0.267

Table 3

Calculated voice connection interruption probability in M/G/1 QSO per TF seconds for an initial file size of 1 MB for G.711 codecs at C = 6 Mbps

Number of users			
500	450	400	350
Probability of all voice connections being interrupted per TF seconds during document file transfers			
0.247	0.0200	0.0158	0.0121

The scientific objective of the study is to develop and analyze a mathematical model for flexible resource management in an access node based on an IP-PBX with heterogeneous traffic, which allows for increased efficiency in bandwidth utilization by routing excess priority traffic between logical segments (slices) of the network.

The wide variety of traffic management strategies can be summarized in three basic models, each with its own advantages and disadvantages [9, 12-15].

Complete Partitioning (CP) systems. In this model, a shared pool of N channels is rigidly divided into segments, each assigned to a specific type of traffic. In the context of our problem, this would mean allocating K channels exclusively to voice traffic and (N-K) channels to file traffic. As V.A. Naumov rightly notes, the main advantage of CP is the complete isolation of services, guaranteeing that "aggressive" file traffic cannot affect voice service.

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However, this approach is extremely inefficient in terms of resource utilization. Under uneven load conditions, typical of real networks, a situation where all channels in one segment are occupied and failures occur, while in another there are available resources, is typical. This leads to excessive requirements for the overall capacity of the system to achieve the specified loss probabilities [4-6].

Complete Sharing (CS) systems. In this model, all N channels form a single pool, available for requests of any type. The CS strategy maximizes channel utilization, since any available resource can be immediately occupied by an incoming request. However, when servicing heterogeneous flows jointly, CS leads to "starvation" of low-intensity traffic with high QoS requirements. Consequently, with the CS strategy, file traffic can monopolize a large portion of the channels, leading to unacceptably high probabilities of voice message loss, which is unacceptable from a quality of service perspective.

To address the shortcomings of CS, priority-based service models were developed. The Russian scientific school has made significant contributions to this field. E.S. Kochkareva has thoroughly studied various priority-based service disciplines, including systems with absolute priority without interruption. In such systems, voice requests have unconditional priority when accessing free channels, and file requests are serviced only when there are no pending voice requests in the system. This effectively protects voice traffic, but leads to a sharp increase in file data transfer times during periods of high voice load. In the extreme case, with a constant voice traffic load close to unity, file traffic can be completely blocked [5, 6].

Recognition of the limitations of classical models has spurred the development of hybrid and adaptive approaches. The idea of dynamically redistributing resources between segments based on current load has been actively explored over the past decade.

In their paper, M.A. Snytkina and A.V. Gorelov propose an adaptive resource management algorithm for 5G networks that recalculates the boundaries between virtual segments in real time based on measured traffic intensity. The authors demonstrate a significant increase in utilization compared to CP. However, such systems are inherently slow and complex to implement, due to the need for continuous monitoring and decision-making [1, 2].

Closer to the topic of our research are models with so-called traffic "overflow." The concept of overflow was initially used in hierarchical communication networks, where calls that could not find a free channel in their zone were routed to neighboring ones [8-10]. In the context of multiservice networks, this idea has been transformed into a conditional access strategy, in which traffic from one class can access resources reserved for another class if certain conditions are met (for example, when the "native" segment is underutilized).

The priority-sharing model with spillover proposed in this study is an extension of these ideas. Its key difference is that two access levels are created for voice traffic: guaranteed (primary segment) and conditional (common segment). File traffic, meanwhile, constantly competes for resources in the common segment with spillover voice traffic. This structure allows for a targeted study of the tradeoff between voice service level and data service efficiency.

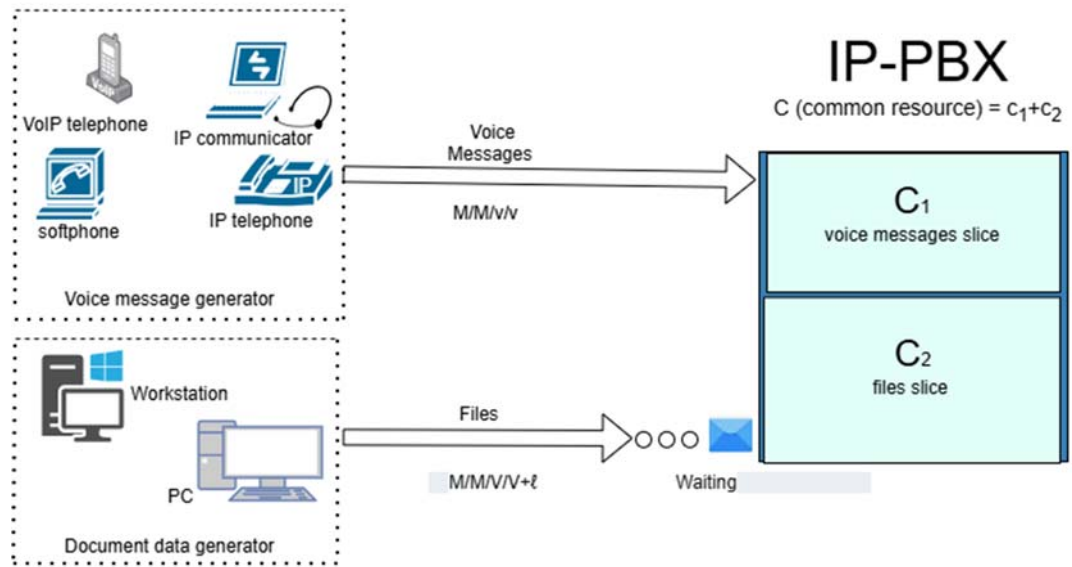
## **5 Network slicing**

Modern communication networks are forced to handle a wide variety of data types simultaneously. Each type has its own stringent connection quality requirements. For example, voice messages dominate real-time traffic and are extremely sensitive to delays. At the same time, high throughput and guaranteed error-free delivery are more important for file transfer.

When all these heterogeneous data streams try to fit simultaneously into channels with limited bandwidth, they interfere with each other, and a fundamental and familiar problem arises: how to most efficiently distribute these resources among competing heterogeneous streams.

There is a traditional method for solving this problem called "Network Slicing."

This is an architectural approach in which a single physical network infrastructure is virtually divided into several isolated logical segments called "slices." Each slice is configured to efficiently handle a specific type of traffic with unique quality of service requirements. Real-time traffic (voice messages) is served in its own dedicated slice. The file request stream is served in a separate, independent slice (Fig. 3).



**Figure 3.** Illustration of the speed resource distribution using the "Network Slicing"

For static allocation, resources (virtual channels) are assigned to each slice on a permanent or long-term basis. Requests received in one slice cannot be redirected to another, even if there are available resources, which can lead to inefficient utilization if the load in one slice is low and in another high.

The model under study represents a more flexible resource sharing scheme. Server resources are explicitly divided into two parts, but there is interaction between them. The isolated slice is intended exclusively for real-time traffic, which is served in lossy mode. If all channels in this slice are busy when a voice request arrives, the request is not immediately rejected.

It should be noted that determining the number of virtual channels in the available speed resource involves using the characteristics of the specific codecs that are supposed to be used.

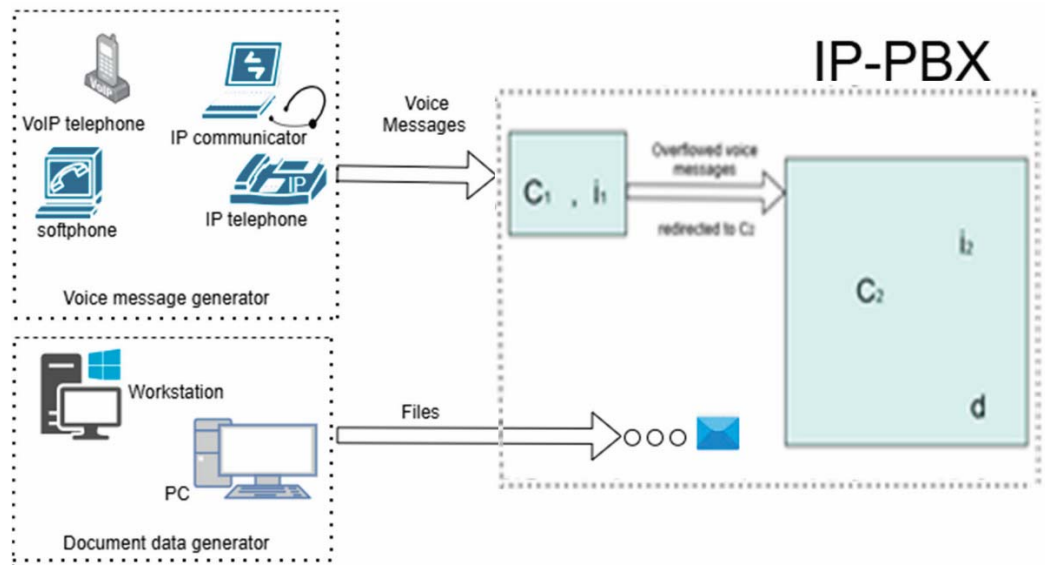
**Redirection Mechanism:** Instead of being rejected, voice requests are redirected as redundant requests to a shared resource slice designated for file traffic slice.

The shared slice is used for file traffic and redundant voice requests redirected from an isolated slice.

Files can wait in the queue, while voice messages have priority service.

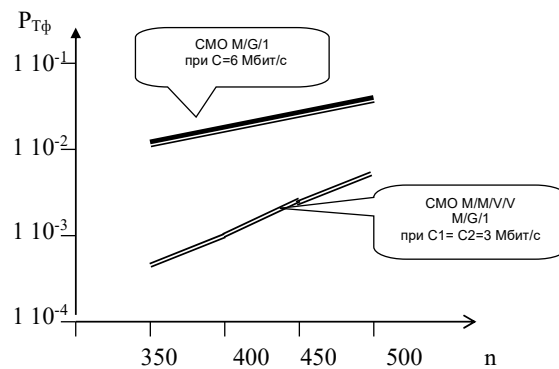
The resources of the shared slice are shared between the two traffic types, improving overall utilization.

The system's structural diagram, shown in Figure 4, visualizes the problem under study. Streams from IP phones and softphones, representing voice traffic, are received for service. A key feature of the model is a priority resource sharing mechanism with spillover: voice messages that are rejected in the primary resource segment can be redirected (spilled) to an additional segment shared with file traffic. This approach reduces the overall probability of voice call loss, but creates complex flow interaction dynamics that require in-depth mathematical analysis.



**Figure 4.** Flexible traffic distribution option between slices

Figure 5 shows the results of calculations of the probability of long interruptions in voice communication from the number of users for the slicing options in Figures 3 and 4.



**Figure 5.** Dependence of the probability of voice communication interruptions per TF seconds on the number of users in an IP-PBX with G.711 codecs for document files of 1 MB, transmitted in whole or in fragments

The calculations confirm the potential of dividing the bandwidth resource on the PBX access section to Internet or IP-MPLS network resources into two streams: voice requests only and mixed traffic consisting of some voice requests (excessive for the first stream) and document files.

### 6 Round robin principle for document file fragmentation

The Round Robin (RR) principle is a fundamental approach to managing resource allocation in computing and network systems, particularly when it comes to multitasking and ensuring fair access to limited resources. The basic idea is to service all tasks or devices in a cyclical fashion, each allocated a time slice to perform the work or a virtual channel resource. When this principle is implemented in an IP-PBX, after a document file fragment is transferred, the access resource is passed to the next element in the queue.

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In terms of its basic principles and mechanisms, Round Robin can be thought of as a circular queue in which each element is a process, a service request. In the classic understanding of RR, each task receives a fixed execution time, after which it is moved to the end of the queue. This approach ensures that no single device can dominate resource utilization, especially in network systems where devices may have different technical characteristics and operating speeds [2-4, 12-17].

The Round Robin principle has found application in the context of data transmission in the latest Wi-Fi standards and in LTE networks, where devices differ in standards and data rates. It allows for the equal distribution of available time and bandwidth among all participants. This is especially important when the network contains both high-performance devices and older devices operating at lower speeds. Without a fair resource distribution mechanism, such devices can slow down the entire system.

One of the key aspects of applying Round Robin in network systems is determining the optimal time slice (in our case, file fragment sizes). If the slice is too small, the system will frequently switch between devices (in our case, between files), which will lead to excessive overhead in managing these switches and, ultimately, can reduce overall performance. On the other hand, if the slice is too large, devices with lower speeds can occupy the channel for extended periods, degrading the quality of service for higher-performance devices.

Therefore, it is important to find a balance that ensures efficient resource allocation and minimal latency. An important aspect of the study is modeling the data transfer process between devices with different technical characteristics. For example, when transferring a 1 MB file between several devices operating under old and new standards, it is necessary to estimate the delays that may occur both with and without Round Robin. Modeling allows us to visualize and quantify how transfer time varies depending on file size and the number of active users.

Resource efficiency under various load levels is a key factor in selecting and configuring the Round Robin algorithm. Under low network load conditions, Round Robin can effectively distribute resources between devices, minimizing delays. However, under high load, especially with a large number of active users, difficulties may arise. Round Robin can be integrated with QoS to ensure fair and efficient distribution of network resources.

## 7 Conclusion

The scientific novelty of the research is as follows.

1. A new architecture for flexible network resource management at the access level is proposed, based on a modified Network Slicing concept with the ability to effectively redistribute traffic between logical segments.
2. An original mathematical model of the operation of an access node with heterogeneous traffic, based on the use of a multidimensional random process, is developed.
3. A comprehensive analytical apparatus is created for studying the steady-state operating modes of the system and evaluating the key performance indicators of servicing heterogeneous data flows.
4. An approach to determining the configuration parameters of individual network segments is substantiated, allowing for achieving a balance between quality of service requirements and bandwidth efficiency.

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# MODELING THE SPECTRUM OF THE OUTPUT SIGNAL TO A RESPONSE SIGNAL GENERATOR FOR A RADIO TRANSMITTER IN AN INTER-SATELLITE COMMUNICATION LINK

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## ABSTRACT

In the modern world, the use of inter-satellite communication links presents engineering challenges: increasing demands on the precision of onboard antenna stabilization and pointing, radio link power potential, interference immunity, and information security, while the protocol organization of space networks becomes more complex. It is also noted that key tasks for such systems include ensuring electromagnetic compatibility, selecting multiple access methods, and rationally distributing functions between onboard systems and the ground control system. With the transition to large orbital constellations of small satellites in low-Earth orbits, typically using high and ultra-high frequency bands, analyzing the requirements for data transmission quality in inter-satellite communication links becomes a determining factor in selecting the architecture of the entire system. This article presents an experiment simulating the spectrum of the output signal fed to a response signal generator. This modeling is necessary to assess whether the generated radio signal meets output power requirements and the permissible level of out-of-band and spurious emissions. At the design stage of a radio transmitter, this allows one to take into account the influence of filter parameters and amplifier operating modes, identify excess spectral components outside the central frequency band, and adjust the device circuit.

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**KEYWORDS:** *Inter-satellite communication link (ISL), radio transmitting unit (RTD), spacecraft, information and telecommunications systems, generator.*

## 1 Introduction

The response signal generator (RSG) is a critically important component designed to generate, filter, and maintain the required signal level at the device's output.

Based on modern requirements for response signal generators, its functional diagram will include a modulator, a secondary power supply, a frequency synthesizer, a multiplier, a waveguide filter, a mixer, and an amplifier.

This article, in particular, presents a possible option for modeling the output signal spectrum in a response signal generator for the further design of a radio transmitting device.

## 2 Requirements for the Design of a Response Signal Generator

Based on the modern technical characteristics of a radio transmitting device for an intersatellite communication link, the following output signal requirements are imposed on the response signal generator:

1. The center frequency at the output is 26260 MHz;
2. The output signal power level should be  $(2 \pm 2)$  dBm;
3. Attenuation of spurious spectral components in the frequency band  $f_{out} \pm 500$  MHz – at least 45 dBc;
4. Attenuation of spurious spectral components in the frequency band  $f_{out} \pm 2$  GHz outside the band  $f_{out} \pm 500$  MHz – at least 50 dBc;
5. Local oscillator frequency suppression must be at least 45 dBc;
6. Two-position phase-shift keying of the output signal  $0 + 180^\circ$ .
7. Requirements for the input voltage of the on-board network supply;
8. The power supply for the response signal generator is provided via a two-wire DC power supply line with a voltage of 25.5 to 32 V. The device consumption from the on-board network is no more than 2 A.

When designing a response signal generator, it is impractical to combine all of the above functional elements in a single structural unit, especially given the high frequency of the output signal.

Secondary power supplies and digital components are significant sources of electromagnetic interference, which can degrade the phase noise and spectral frequency of the synthesizer and master oscillator signals, as well as increase intermodulation distortion in the gain path. Separating sensitive components will provide better shielding of the microwave section.

The 26.26 GHz frequency requires the use of specialized microwave substrates. Combining all components in a single unit will lead to technological difficulties, increased losses, and degraded matching.

Based on the above, we propose dividing the response signal generator into two blocks, using the design shown in Figure 1 as a basis. The first block includes a secondary power source, a modulator, and a frequency synthesizer. The second block includes a master oscillator, a frequency synthesizer, and provides frequency conversion to 26.26 GHz.

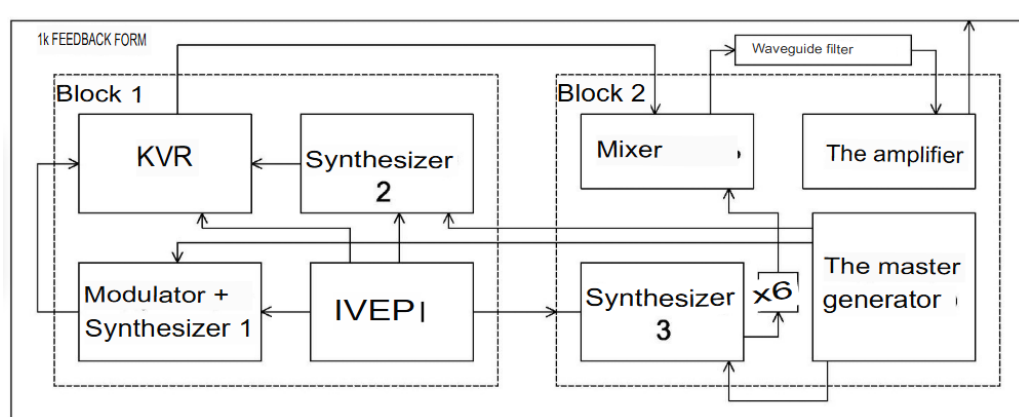


Figure 1. Response signal generator (RSG)

The two response signal generator sub-units are equipped with two control boards. They execute commands received through the switching board, generate control signals, collect and generate telemetry, and trigger automatic protective responses.

### 3 Spectrum Modeling Experiment and Substantiation of Requirements for Its Implementation

In this article, spectrum modeling was performed in the Genesys automated design environment. Using models of microwave paths, filters, and nonlinear amplifiers, this allowed us to obtain a spectrum image close to real-world conditions and construct a level diagram.

Figure 2 shows the block diagram of the second block, the response signal generator, with the specified input parameters of the signal from the output of the first block and the frequency synthesizer (FS). However, in this circuit, filters have been replaced with attenuators in order to demonstrate the signal spectrum in the absence of filtering.

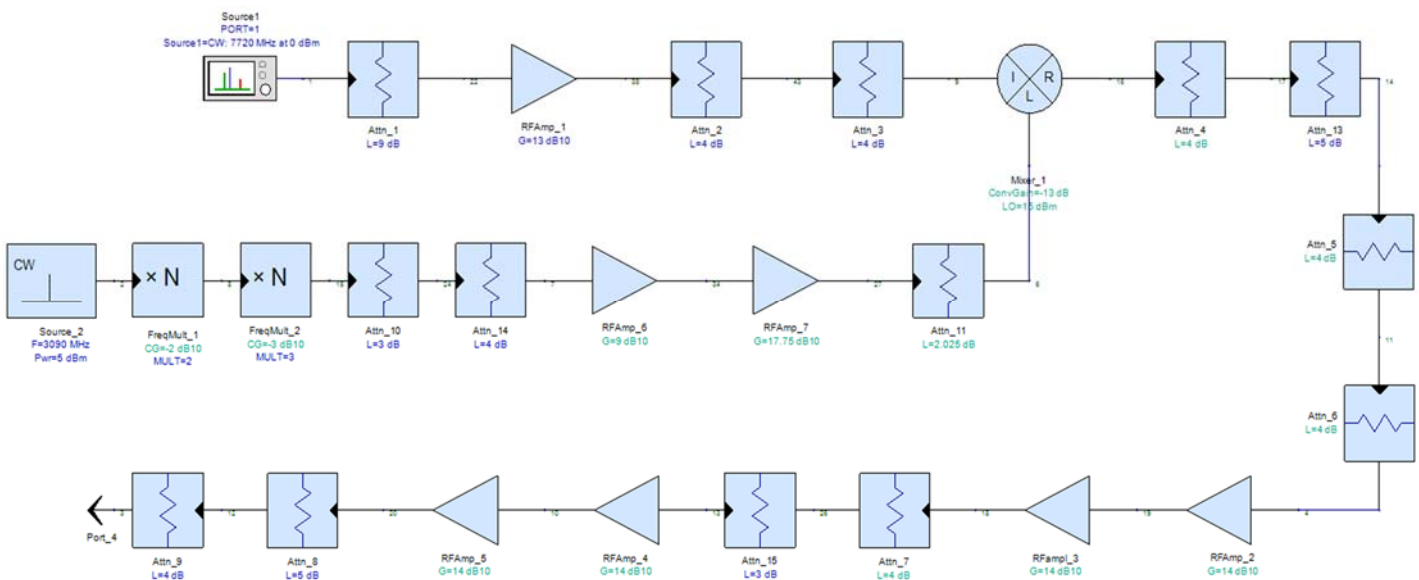


Figure 2. Structural diagram without filters

Figure 3 shows the result of modeling the spectrum at the output of the response signal generator without filters.

Figure 4 shows the structural diagram of the second block of the response signal generator with the characteristics of the selected filters entered.

Figure 5 shows the result of modeling the spectrum at the output of the response signal generator using the selected filters. This demonstrates that the filters were selected correctly. The modeling result meets modern requirements.

Figure 6 shows the level diagram of the presented structural diagram.

System1 PWR at Node 3

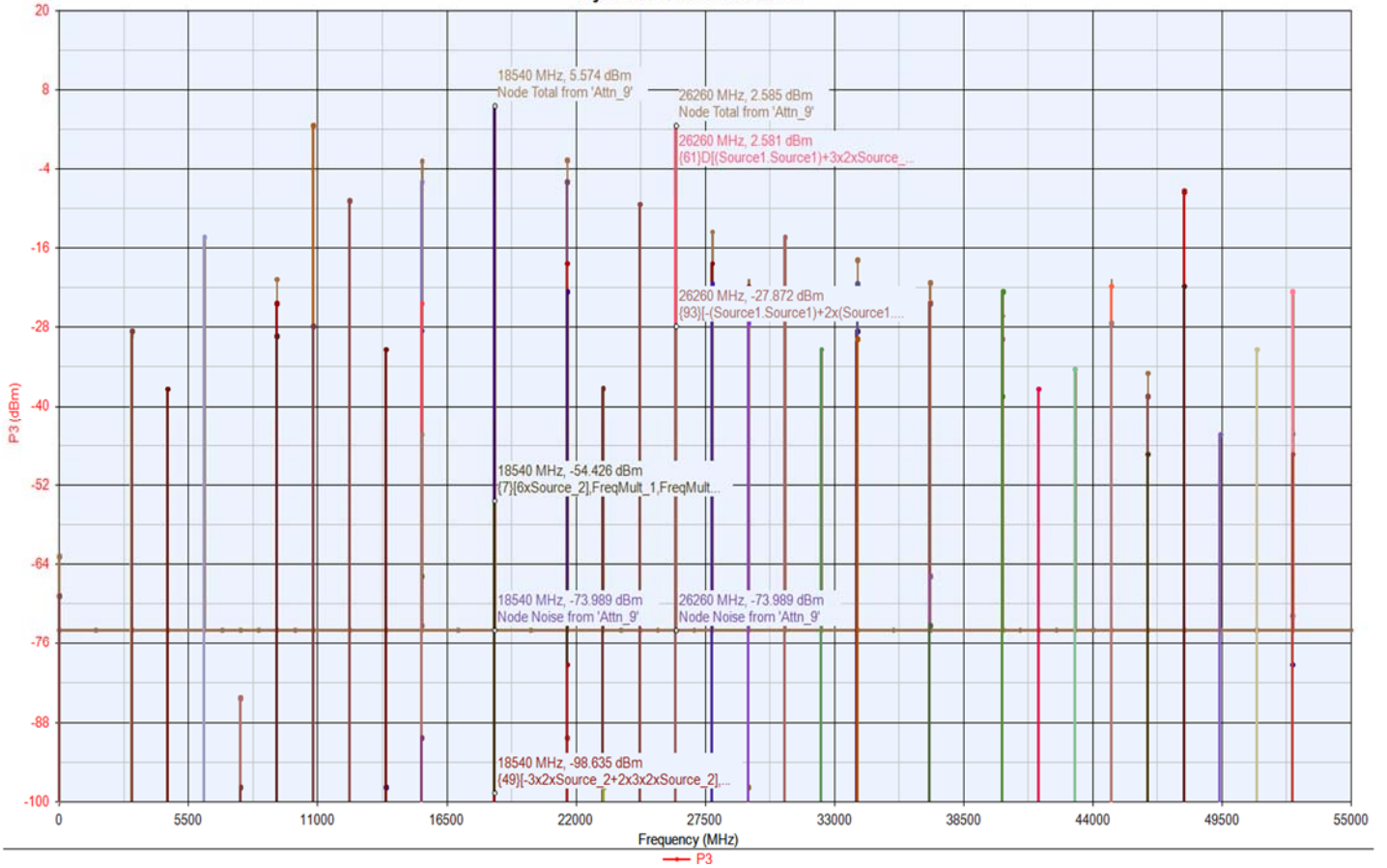


Figure 3. Signal spectrum without filters

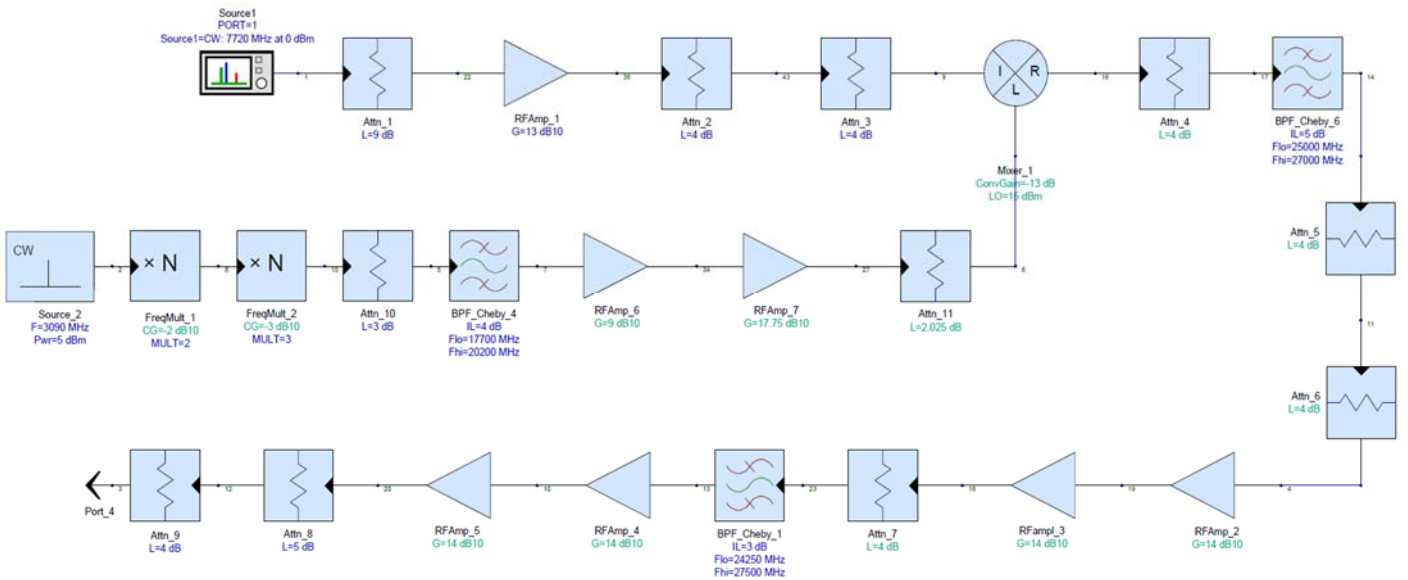


Figure 4. Structural diagram with filters

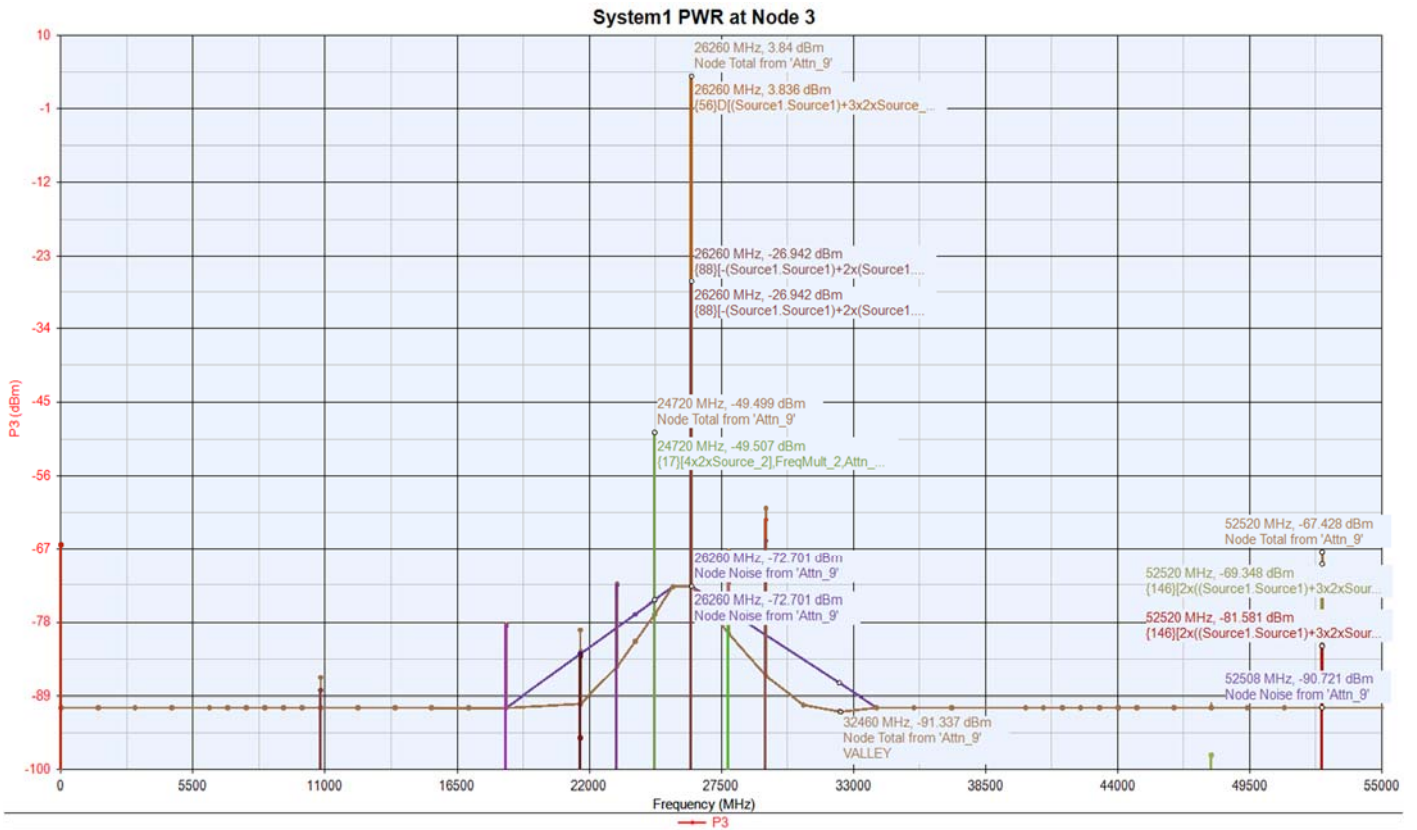


Figure 5. Signal spectrum at the output of the response signal generator

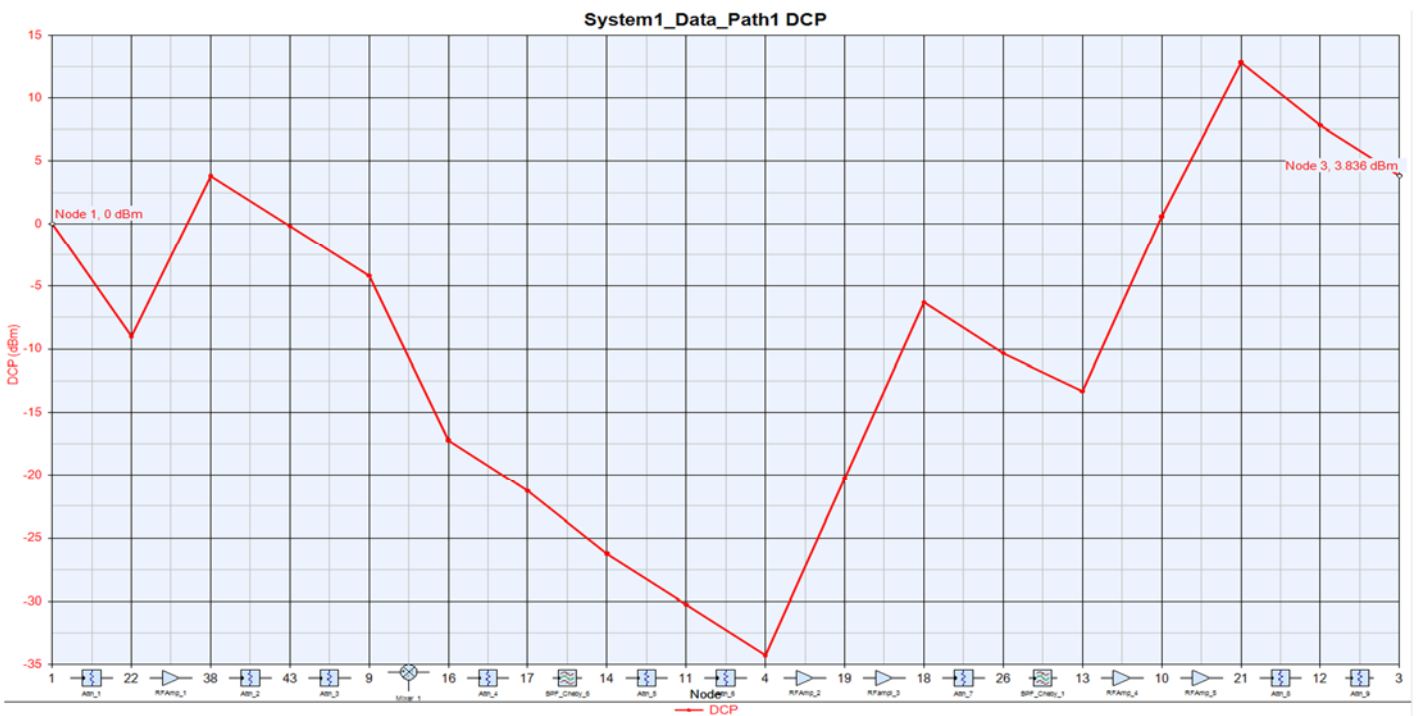


Figure 6. Level diagram

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## 4 Conclusion

Thus, this article plans an experiment to model the output signal spectrum of a response signal generator and substantiates the requirements for its implementation.

The objective of modeling the output signal spectrum of the response signal generator is defined, and the modeling results confirm the correctness of the filter selection and compliance with modern requirements.

The modeling of the output signal spectrum of the response signal generator is performed. It is confirmed that the selected filters and the path structure provide the required suppression of spurious and out-of-band components. The modeling results confirm the correctness of the adopted circuit design solutions.

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# DIFFERENTIATED CONNECTIVITY SERVICES IN 5G STANDALONE ARCHITECTURE

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## ABSTRACT

Standalone is a 5G network construction technology in which the network is deployed on completely new hardware with a separate core. This contrasts with Non-Standalone (NSA) mode, in which the 5G network is deployed on existing 4G network infrastructure (LTE is used for connection management, and 5G for data transmission). This technology enables the full benefits of fifth-generation networks: high mobile internet speeds, ultra-low latency, and more reliable connections. It supports high-density deployments, such as IoT scenarios with dense populations of sensors and controllers in smart buildings, ensuring full next-generation capabilities. This review is based on the "Ericsson Mobility Report 2025" and considers differentiated connectivity services in 5G standalone architecture, speed-based FWA offerings, standardization issues for 6G, the global momentum in commercial differentiated connectivity services, and modernizing enterprise IT with 5G. The result is a more dynamic balance, where networks must support both the growing appetite for real-time cloud and the efficiencies that keep bandwidth use sustainable. Understanding this interplay is key to preparing for the next wave of connected intelligence. The convergence of AI, cloud computing and mobile technologies represents one of the most transformative shifts in the digital era. Together, they create a powerful ecosystem where intelligence, scalability and accessibility reinforce each other: cloud platforms provide the computational infrastructure and storage capacity needed to deploy and train advanced AI models; mobile devices serve as both a data feed and the end-user interface to deliver these AI-powered cloud services, enabling personalized and context-aware experiences in real time; and networks provide ubiquitous and dependent connectivity between cloud and devices.

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**KEYWORDS:** *Standalone, 5G, 6G, artificial intelligence, FWA, cloud computing, mobile technologies.*

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## 1 Introduction

Differentiated communications services in the standalone 5G architecture is a concept that allows operators to offer services tailored to the specific needs of consumers and enterprises. It is implemented through network slicing. Independent virtual segments (slices) are created on a single physical connection for different services or clients. Within a segment, the user is guaranteed the connection parameters they require - speed and latency - regardless of the overall network condition.

The purpose of network slicing is to provide dedicated virtual circuits that prioritize differentiated connection characteristics [7]. Some of these include:

- uplink and downlink bandwidth;
- latency;
- enhanced security and traffic isolation.

A single network slice can serve multiple applications if they have similar connectivity requirements. For example, a slice optimized for high downlink bandwidth can support ultra-high-definition video streaming (4K and above) and large-scale file transfers.

Service providers can monitor and scale the throughput of each segment to optimize network utilization.

Some use cases for which network segments are created:

- High-speed data services for consumers;
- Reliable, low-latency connections for mission-critical industrial applications;
- Massive Machine-to-Machine Communications (mMTC) – for devices where autonomy and a large number of network connections are essential (e.g., water, gas, and electricity meters, street lighting controllers).

Dedicated network segments for mission-critical applications, such as police departments, where flexibility and quality of service are essential.

The implementation of differentiated communications services in a standalone 5G architecture is regulated, for example, by the ITU recommendation IMT-2020 – a set of global technical standards for 5G. The recommendation defines the use cases for which network segments are created and the service performance requirements.

Network Functions Virtualization (NFV) is also used to implement network segments. This allows software to be installed on virtual machines deployed on a virtualized commercial server.

The concept of differentiated communications services in a standalone 5G architecture enables flexible and scalable deployment of services tailored to various scenarios. For example: Live broadcasting in crowded areas, where services can be tailored to audience needs.

A specialized network service for police departments that ensures flexibility and quality of service, increasing the effectiveness of law enforcement officers on the ground.

A dedicated network layer for critical communications, including internal corporate communications.

In 2025, the telecommunications industry made significant strides in deploying 5G standalone (SA) architecture, which is essential for supporting differentiated communications services.

The number of service providers deploying 5G SA has increased globally, with many companies moving from conceptual developments to commercial offerings based on 5G network slicing.

During the third quarter of 2025, 162 million 5G subscriptions were added, bringing the total to almost 2.8 billion - approximately one-third of all mobile subscribers worldwide. The share of traffic carried over 5G continues to grow, and by 2031, more than 1.2 billion people worldwide will be served by 5G fixed wireless broadband. 5G services are impacting the lives of people worldwide [1].

5G connectivity can simplify enterprise IT architecture while supporting zero-trust workflows and leveraging artificial intelligence (AI), which improves security and productivity.

5G-based solutions are reaching entirely new segments.

As for the next generation, the 6G standardization process has already begun. The first commercial launches are expected to be led by leading service providers in advanced markets. 6G networks, originally designed for artificial intelligence, along with new capabilities such as integrated sensing and communications (ISAC), will enable entirely new use cases and device classes.

The highest 5G subscription penetration is expected to be in North America with 79%, followed by North East Asia at 61% and Western Europe and the Gulf Cooperation Council (GCC) countries, both at 55%. Globally, 5G is anticipated to overtake 4G as the dominant mobile access technology by subscription by the end of 2027, nine years after launch [6].

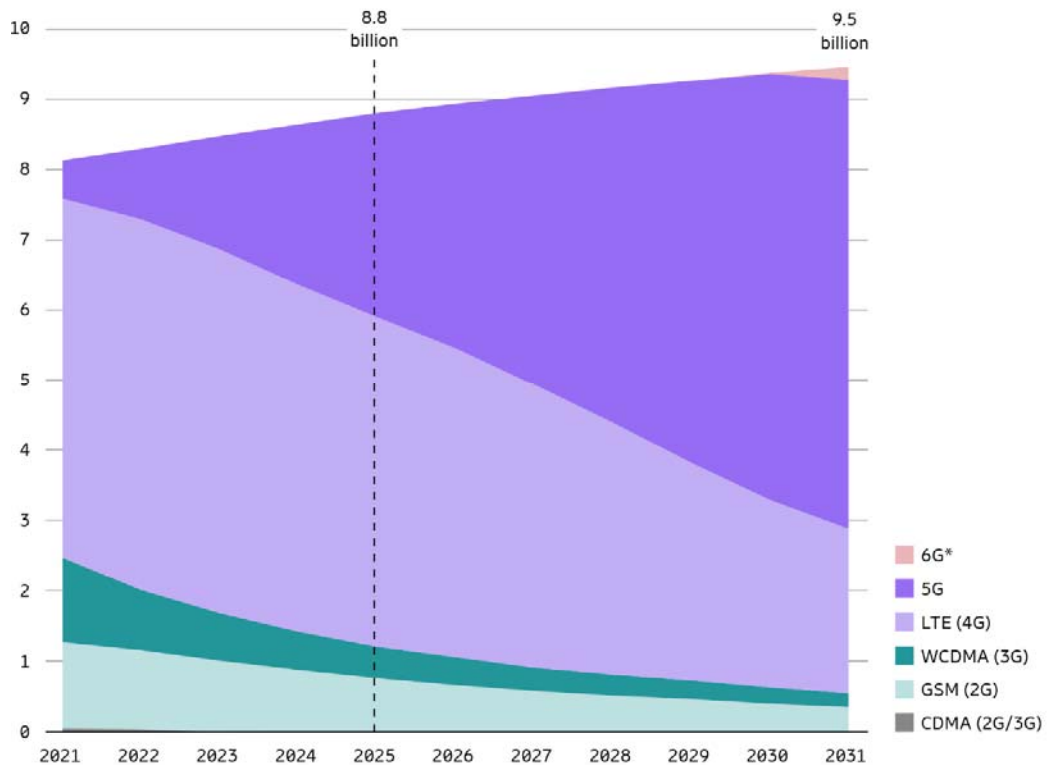
Around 360 service providers have now launched commercial 5G services, and more than 90 of those have launched or soft-launched 5G standalone (SA).

As subscribers migrate to 5G, the number of 4G subscriptions continues to decline. During the third quarter, 4G subscriptions declined by 65 million, bringing the total below 4.8 billion. 3G subscriptions declined by 22 million during the same period, while 2G subscriptions dropped by 29 million.

2G and 3G network sunsetting continues around the world. The phasing out of 3G networks is anticipated to happen more quickly than that of 2G in the coming years, but the timeline for this transition varies based on country and service provider.

Two-thirds of all mobile subscriptions expected to be 5G at the end of 2031. Global 5G subscriptions are forecast to reach 6.4 billion in 2031 and will make up two-thirds of all mobile subscriptions. Deployment of 5G SA by leading service providers will continue, and 5G SA subscriptions are projected to account for more than 4.1 billion in 2031, making up around 65% of all 5G subscriptions at that time.

In 2031, it is projected that Western Europe, North America and the GCC countries will have 5G subscription penetration of above 90%.



**Figure 1.** Mobile subscriptions by technology (billion).

\*does not include early uptake of AI-enabled IoT devices such as autonomous vehicles, smart glasses and drones [1]

The following technologies are used to implement differentiated services in 5G networks:

- Massive MIMO. Using this technology, telecom operators can ensure full 5G network coverage, improve service quality, and reduce costs.

- 
- Dynamic Spectrum Sharing (DSS). Spectrum resources are allocated in milliseconds depending on LTE and 5G services and the required traffic.
  - Network Function Virtualization (NFV). 5G functions are implemented in virtual network functions (VNFs) that run on the NFV infrastructure.
  - Software-defined networking (SDN). Aimed at creating flexible and scalable networks, sharing physical infrastructure with virtual overlays, and automating network management and administration.
  - Adaptive antennas with BeamForming technology. Enable direct communication between devices, thereby reducing interference between devices.
  - Support for stateless network functions. 5G network functions do not store user and session data internally, accessing it from external storage when needed. This approach increases network flexibility and resiliency [4, 5].
  - Edge Computing. Large volumes of data are analyzed and processed directly at their source – from industrial sensors to autonomous vehicles – using AI, eliminating the latency of cloud data centers.
  - Use of digital twins. This technology allows companies to model all network scenarios, enabling proactive network maintenance and moving from passive response to proactive prevention and ensuring continuous service access.

## 2 Standardization for 6G

3GPP Release 21, based on ITU IMT-2030. 6G is expected to have only a standalone architecture with a core network built on the architectural principles of 5G SA, extended with new capabilities such as AI and integrated sensing and communication (ISAC). A new Radio Access Network (RAN) architecture will be defined, including a new radio interface. For traditional use cases like enhanced mobile broadband (eMBB), Fixed Wireless Access (FWA) and the Internet of Things (IoT), 6G will advance the performance, service differentiation and guarantees. As these network technologies open up new service possibilities, use cases like massive digital twinning, autonomous mobility and wide-area mixed reality are likely to gain broader commercial adoption [7-9].

Global 6G subscriptions<sup>3</sup> are forecast to reach 180 million by the end of 2031, not including early uptake of AI-enabled IoT devices such as autonomous vehicles, smart glasses and drones. If 6G subscription uptake happens earlier, the current forecast could be surpassed significantly [1]. The timing of commercial launch will vary between regions and countries:

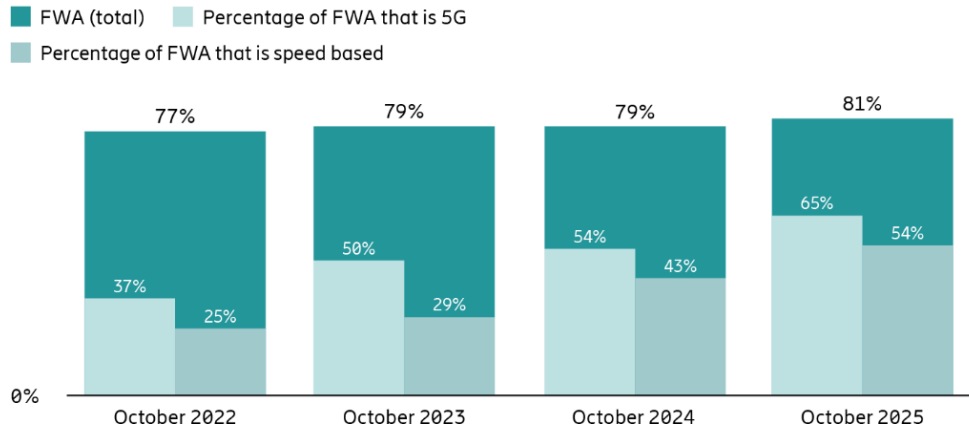
- In the US, China, Japan, the GCC countries and South Korea, the launch of commercial 5G services took place relatively early compared to many other countries, and it is expected that these countries will be among the first to roll out 6G commercial services.
- India has been vocal in its ambition to lead in 6G technology, and it is expected that the timing of the commercial 6G launch compared to other countries will happen earlier than it did for 5G.
- In Europe, the launch of commercial 6G services is anticipated to be about one year later, relative to other countries, than was the case for 5G, due to the later roll out of 5G SA.

In recent years, there has been a growth will all be crucial to support an in satellite networks. Globally, large constellations of low-Earth satellite broadband subscriptions are orbit (LEO) satellites [3]. These networks forecast to increase from around can provide multiple services such as 9 million by the end of 2025 to around direct-to-device connectivity and fixed 30 million by the end of 2031. For broadband internet (that is, fixed comparison, there will be a projected satellite services). To meet the 350 million FWA subscriptions on fixed broadband connectivity needs mobile networks by 2031. The total as we approach 2031, the mix of fiber, number of fixed broadband connections 5G FWA and satellite technologies will be around 2 billion by 2031.

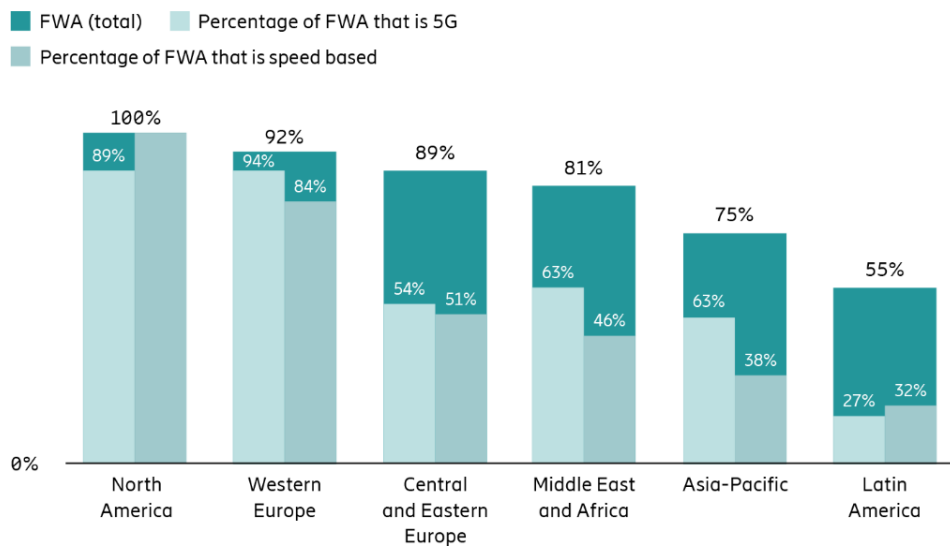
## 3 Speed-based FWA offerings

Service providers are capitalizing on consumer preferences for fast, reliable services; the proportion of Fixed Wireless Access (FWA) service providers offering speed-based tariff plans has increased from 43 to 54% in one year.

Figure 2 shows the block diagram of the second block, the response signal generator, with the specified input parameters of the signal from the output of the first block and the frequency synthesizer (FS). However, in this circuit, filters have been replaced with attenuators in order to demonstrate the signal spectrum in the absence of filtering.



**Figure 2.** Global FWA service provider adoption 2022-2025



**Figure 3.** Regional FWA service provider adoption 2025

Over half of FWA service providers now offer speed-based tariff plans. Speed-based tariff plans are commonly offered for fixed broadband services, such as those delivered over fiber or cable (offered by 54% of FWA service providers, up from 43% a year ago). The remaining 46% offer only volume-based tariff plans (buckets of GB per month).

FWA adoption is widespread globally. Number of service providers offering speed-based plans, driven primarily by Western Europe. Latin America has the most potential.

There is robust demand for FWA in India, with the combined number of connections from Jio and Airtel reaching 12 million as of September 2025.

In the US, the three largest service providers achieved all-time-high quarterly FWA net adds of 1.04 million connections in Q3 2025. As a result, their combined FWA user base stands at 14.6 million connections.

High-growth markets are leveraging FWA to drive revenue expansion. For example, Smart Philippines reported a 12% year-on-year increase in 5G FWA connections, with FWA revenues emerging as the fastest-growing segment of mobile revenues with an increase of 22% year-on-year.

A recent FWA customer premises equipment (CPE) survey, which encompasses insights from 17 leading vendors, projects shipments of 35 million CPE units in 2025, representing a 26% year-on-year growth. Notably, 57% of these shipments are expected to be 5G-capable.

Cosmote, Greece, has introduced differentiated 5G FWA connectivity, reaching 19,000 connections at the end of Q2 2025. This enabled the total fixed broadband segment to achieve growth and reverse the negative trajectory seen from previous quarters.

In the US, FWA is a major factor in 5G standalone (SA) traffic growth, primarily driven by leading service providers.

Markets with strong 5G FWA growth excel in two areas:

- 5G deployment maturity: Characterized by broad 5G population coverage, in particular 5G mid-band coverage, as well as adoption of 5G SA and 5G Advanced.

- FWA monetization maturity: Refers to a variety of 5G FWA offerings, in particular speed-based FWA such as tiered speed plans. More advanced service providers are offering a premium experience FWA based on differentiated connectivity.

Considering a global average household size of about four people, this equates to approximately 1.4 billion individuals being served by FWA broadband by the end of 2031. Half of global FWA connections to be in Asia-Pacific by 2031. Higher volumes of 5G FWA in populous, high-growth countries can drive economies of scale for the overall 5G FWA ecosystem, resulting in even more affordable CPE.

Asia-Pacific's share of global FWA connections is expected to increase from just over 40% in 2025 to 50% by 2031.

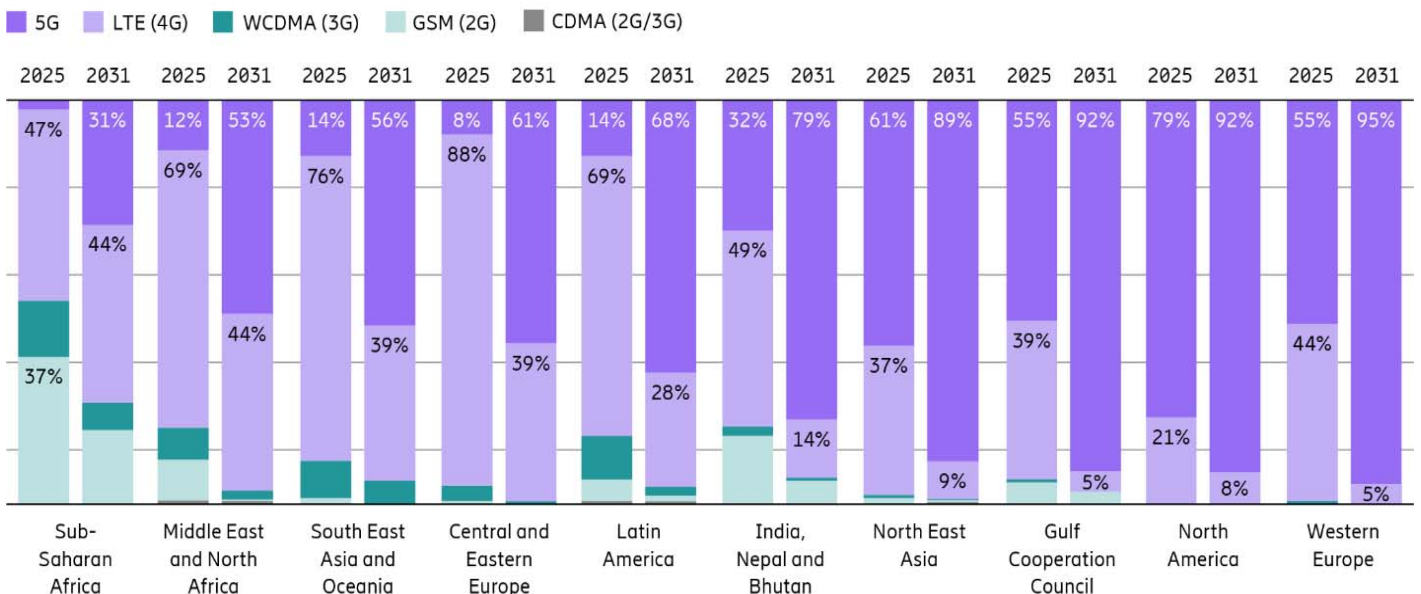


Figure 4. Mobile subscriptions by region and technology (percent)

### Sub-Saharan Africa

The ongoing rollout of 4G and the early stages of 5G deployment are expected to gradually phase out legacy technologies. Sunsetting of 3G networks is anticipated to happen sooner than for 2G networks, with 3G subscriptions expected to decline by 8 percent annually over the forecast period, to a total of 89 million in 2031. 2G subscriptions are projected to fall by 7% annually to a total of 243 million. In 2031, 4G is set to account for 44% of all mobile subscriptions, while 5G is expected to grow significantly to around 400 million subscriptions. Smartphone subscriptions are projected to rise to 960 million in 2031. Notably, around 42% of these are expected to be 5G subscriptions, reflecting the growing consumer demand and evolving mobile ecosystem.

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### ***Middle East and North Africa***

Regional efforts to diversify economies and drive digital transformation are helping to stabilize the sector and sustain investment momentum. Mobile subscriptions are projected to grow at an annual rate of 1% up to 2031, reaching a total of 780 million. Notably, 5G subscriptions are forecast to rise with a CAGR of around 30 percent over the same period, signaling a shift in how users engage with digital services. In 2031, 4G is anticipated to make up 44% of mobile subscriptions, while 5G is set to dominate with 53% of the total subscriptions. 5G FWA is also gaining traction as a key enabler of next-generation connectivity, complementing traditional broadband offerings.

### ***South East Asia and Oceania***

5G subscriptions in the region are forecast to reach around 680 million in 2031. 5G is evolving beyond coverage to prioritize performance, differentiated connectivity and high-value use cases. Service providers across the region have launched experience-led differentiated connectivity offerings, such as boost packs and network slices, for consumers and enterprises.

Singapore offers tiered 5G experiences for consumers and enterprises, delivering differentiated connectivity based on user needs for speed, priority and security.

Meanwhile, Australia is rolling out service level agreement-backed 5G for mission-critical enterprise workloads. In Malaysia, network slicing capabilities are now available for 5G consumers.

5G has become a significant driver of data consumption and increased ARPU in Thailand, with service providers reporting 10–15% ARPU uplift among 5G users. Vietnam's government is driving accelerated 5G deployment of 90% population coverage in 2025, through a mix of targeted subsidies for service providers and spectrum reforms.

### ***Central and Eastern Europe***

Technology adoption and subscription uptake has historically been slower here than in Western Europe. 5G deployment varies by country, partly due to slower spectrum allocation processes. However, the region has seen several accelerated 5G deployments, driven by growing demand. For example, Croatia leverages 5G for tourism and smart cities, while 5G in Hungary is going beyond smartphones to the automotive sector and other use cases. Regionally, 5G subscriptions are expected to reach 45 million during 2025. 4G is currently the dominant technology and is expected to account for 88% of all subscriptions at the end of 2025. It is estimated that this share will decline after a peak in 2025, as subscribers migrate to 5G.

### ***Latin America***

5G is gaining momentum in Latin America after a slow start. Although the region currently has a small base with 106 million 5G subscriptions, the large overall subscriber base is projected to enable Latin American 5G subscriptions to reach 553 million by the end of 2031. Throughout this period of growth in number of 5G subscriptions, the mobile infrastructure is anticipated to mature significantly with the adoption of 5G standalone (SA) architecture, 5G Advanced technologies, network slicing and open programmable architectures. This will fuel digital transformation in the region.

### ***India, Nepal and Bhutan***

5G adoption in India is growing rapidly. The expansion of 5G networks, availability of affordable 5G FWA customer premises equipment (CPE) and high data consumption from FWA users is fueling the data traffic growth in India. 5G FWA allows for rapid deployment of broadband services to homes and businesses, especially in rural and semi-urban areas where fiber optic cable installation is slow and expensive, and is helping to bridge the digital divide. Regionally, 5G subscriptions are expected to reach 394 million at the end of 2025, accounting for 32% of total mobile subscriptions. More than 1 billion 5G subscriptions are expected by the end of 2031, reaching 79% subscription penetration. 4G is currently the dominant subscription type, making up 49% of total mobile subscriptions. 4G subscriptions are forecast to decline from around 600 million in 2025 to around 190 million in 2031, as subscribers migrate to 5G.

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### **North East Asia**

The region has the second-highest 5G subscription penetration globally, and is expected to reach 61% at the end of 2025. Adoption of differentiated connectivity is expanding across the region, enhancing user experience and creating opportunities for service providers to monetize personalized services. In mainland China, 5G subscriptions are expected to reach 1.2 billion at the end of 2025, and over 90% of smartphone shipments are anticipated to be 5G-capable.<sup>1</sup> 5G Advanced is becoming more widely available, including functionalities such as support for reduced capability (RedCap) and high-order carrier aggregation [2].

In Japan, progress in 5G SA is improving consumer experiences, and service offerings that leverage differentiated connectivity are emerging. Service providers are also increasing investments in areas such as AI, to support future monetization strategies. South Korea continues to offer high average 5G throughput while expanding coverage, including in rural areas, through network sharing. Service providers remain focused on improving user experience and preparing networks for increased importance in the AI era, alongside efforts to monetize 5G services.

In Hong Kong, service providers report a substantially increased ARPU from 5G compared to 4G, contributing positively to financial performance. In Taiwan, service providers have begun testing differentiated connectivity offerings in specific segments, such as live entertainment, with commercial 5G SA services expected to launch within the next one to two years.

### **Gulf Cooperation Council (GCC)**

The region, while small in terms of subscribers, is notable for its high penetration, high levels of urbanization and robust consumer spending power. Service providers are transitioning from traditional telcos to digital service providers. This is enabled by extensive 5G deployment and the adoption of technologies such as AI, cloud computing and edge solutions. Network slicing, supported by programmable networks and open APIs, is expected to be a cornerstone in delivering customized and performance-sensitive services.

In 2031, mobile subscriptions are expected to reach 97 million. Subscriptions for legacy network generations will decline sharply as users migrate to next-generation connectivity. By the end of 2031, 5G subscriptions are expected to comprise 92% of all mobile subscriptions, totaling 89 million. FWA adoption is driven by demand for high-speed alternatives to fixed broadband and national initiatives aimed at reaching underserved areas and supporting smart-city ambitions.

### **North America**

5G subscriptions are expected to reach 359 million at the end of 2025, accounting for 79% of all mobile subscriptions at that time, and to further reach around 450 million in 2031. Leading service providers anticipate continued growth for FWA and are introducing differentiated connectivity to offer tailored experiences. Extensive mid-band 5G network coverage is the foundation for new consumers, enterprises and government innovations across the broader tech ecosystem. The innovations are created at the intersection of AI, cloud and mobile.

### **Western Europe**

5G subscription growth is strong in the region, and is expected to rise from 227 million at the end of 2024 to 307 million in 2025, equaling a penetration of 55%. 5G subscription penetration varies between countries, where markets that launched 5G early, such as the UK and Finland, have already achieved high penetration relative to other markets. Going forward, 4G is expected to decline in favor of 5G. 5G subscriptions are anticipated to reach around 540 million at the end of 2031, representing 95% penetration at that time, which is in line with other leading 5G markets. 5G mid-band and SA are gaining traction in the region, with leading service providers launching new offerings based on differentiated connectivity in areas such as payment terminals, live broadcasting and photojournalism.

## **4 5G standalone**

5G standalone (SA) is playing a central role in improving wearable devices. Smartwatches are leading this development with integrated connectivity, with smart glasses expected to follow in the future.

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Some benefits of differentiated services:

- Providing higher quality to those services that require it for a better user experience.
- Avoiding inefficient resource usage by selecting a configuration that best suits a specific service based on customer needs.
- Simplifying network operation.
- Scalability, as resource allocation is based on the granularity of the class.
- Eliminating the need to upgrade applications for use on a differentiated services network, unlike networks with integrated services.

#### ***RedCap wearables supported by 5G SA***

The first widely used smartwatch supporting 5G SA reduced capability (RedCap) is now supported by over 20 service providers, underscoring a growing focus on 5G SA-enabled devices. Although wearables cannot compare in sales volume to smartphones, they may have an important role in the future device ecosystem. Device manufacturers selecting 5G SA with RedCap for devices requiring long battery life confirms that the 5G SA era is here, with the rest of the ecosystem expected to follow.

#### ***Smart glasses in the 5G era***

Lightweight smart glasses typically connect to the cellular network through a companion device, such as a smartphone, but integrated connectivity is expected in the next two to three years. RedCap can play an important role here, providing the size and power efficiency required for this form factor. Companion devices will continue to be important for offloading compute from the glasses, but edge computing is expected to be the way forward. Early adopters of AI/AR glasses report benefits such as the simplicity of hands-free phone calls and use of the simple screen for incoming messages.

The question of whether smart glasses will ultimately replace smartphones remains: Currently, sales volumes are less than 1% of smartphones.

#### ***Growth of 5G SA-only devices***

In China, there is a growing trend toward 5G SA-only devices to reduce cost and increase simplicity. This trend is expected to drive demand for SA roaming, as most service providers today rely on non-standalone (NSA) when subscribers roam. Without SA roaming, these devices will need to fall back to LTE when abroad.

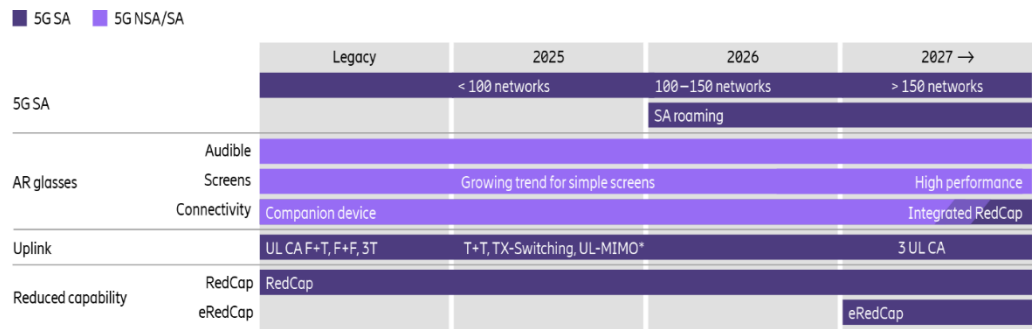
#### ***Boosting uplink performance***

The smartphone industry is increasingly focusing on uplink performance. Some commercial smartphones now include support for uplink carrier aggregation (CA), combining frequency division duplex (FDD) and time division duplex (TDD) frequency bands to boost capacity and performance. Certain models also support uplink Multiple-Input Multiple-Output (MIMO), enabling the simultaneous transmission of data over several antennas, increasing uplink speed and reliability.

A few devices implement Release 16 uplink transmit (TX) switching, a feature that lets the smartphone intelligently switch between uplink antennas depending on signal conditions, providing improved connection stability and energy efficiency. However, adding more uplink capabilities to the smartphone can introduce size, complexity, cost and battery performance challenges. For Fixed Wireless Access (FWA), there is a concurrent trend to increase output power to strengthen the uplink signal. Overall, the intensified focus on uplink aligns with today's demanding user behavior, where people upload content more than ever before.

#### ***EVs and drones driving 5G innovation***

Smartphone vendors and established chipset vendors are now investing in the electric vehicle (EV) sector. As cars offload more computational tasks, their data consumption increases. Self-driving taxis, for example, rely on reliable connectivity that can be further enhanced using network slicing. The low-altitude digital airspace ecosystem, particularly the drone segment, is becoming an important market for 5G connectivity, with 5G SA enabling digital services that enhance cost-efficiency and support weight requirements of drones.



**Figure 7.** 5G technology area readiness on device

Note: Readiness means more than one infrastructure and device vendor is ready. Key terms: carrier aggregation (CA), F+T (FDD and TDD), F+F (FDD and FDD), T+T (TDD and TDD), TX-switching (antenna switching), UL-MIMO (2TX antennas in uplink), 3 UL CA (3 uplink carrier aggregation). \*Limited market use ahead of timeline

Mobile network data traffic continues to grow. Global mobile data traffic, excluding Fixed Wireless Access (FWA), is projected to increase by a factor of around 2.2 to reach 310 EB per month in 2031.

The share of mobile data carried over 5G is forecast to rise from 34% at the end of 2024 to 43% by the end of 2025, reaching 83% in 2031. In 2031, a 14% year-on-year growth rate is expected, with a CAGR of 16% over the full forecast period. Total global mobile data traffic generated by 6G subscriptions is expected to be limited in 2031, due to the relatively low number of such subscriptions compared to 5G at that time.

Mobile data traffic growth can be highly volatile and vary significantly between years, regions, markets and service providers, depending on local market dynamics.

Factors that could impact traffic growth include:

- The uptake rate of new devices, such as those built for AR, and scalable, multimodal generative AI (GenAI) applications. The current predicted traffic growth up to 2031 includes an assumption that an initial uptake of extended reality (XR) services, including AR, VR and mixed reality (MR), will happen in the latter part of the forecast period. However, if adoption is accelerated, data traffic could significantly surpass current traffic outlook at the end of the forecast period.

- Tariff plans and available services.
- Continued improvements in the performance of deployed networks.
- The pace of subscriber migration to later mobile technology generations in populous markets like India, Latin America, South East Asia and Africa.
- Changes to the split between FWA and mobile data traffic when FWA connections grow.

With continued strong FWA uptake in parts of the world where fixed broadband connections have been limited, it is likely that household-based traffic will move from smartphones to FWA – especially for streaming services.

The growth in mobile data traffic per smartphone can be attributed to several drivers: improved device capabilities, affordable service plans, increased time spent consuming services, an increase in data-intensive content, and growth in data consumption due to continued improvements in deployed network performance.

During 2025, these factors affected mobile data traffic differently across several countries:

- In Brazil, mobile data prices rose by around 20%, driving data traffic growth rate down.
- In China, intensified competition among service providers supported growth in mobile data traffic.
- In South Korea, mobile data traffic reached double-digit year-on-year, driven by a larger share of data-intensive content.
- In India, traffic growth increased year-on-year, supported by improved device capabilities.

Traffic growth is not universal across locations within a service provider's network. For example, in dense urban locations, traffic demands can be up to 1,000 times larger relative to rural areas.

Average mobile data traffic per active smartphone is 21 GB globally in 2025.

- Smartp one shipment volumes in different regions.

Total 5G coverage outside mainland China is expected to increase from 45 to 50% during 2025, while mid-band coverage is projected to grow from 40 to 45% over the same period.

There are currently 841 4G networks deployed worldwide, with 347 upgraded to LTE-Advanced and 448 LTE devices supporting Cat-16.1 By the end of 2025, 4G population coverage outside mainland China is set to reach 90% globally and is projected to exceed 95% in 2031.

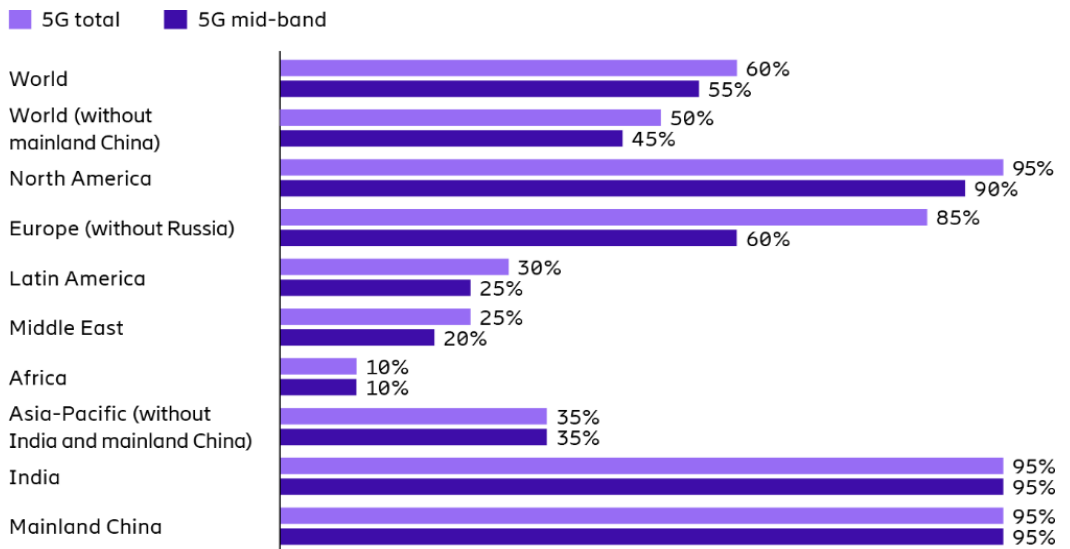
The build-out of 5G continues, with around 360 networks launched worldwide. Outside mainland China, it is projected to increase from 50% in 2025 to about 85% in 2031.

5G mid-band, either delivered through time division duplex (TDD) or frequency division duplex (FDD), combines high capacity with good coverage. It is available in most markets, making it an ideal choice for delivering the full 5G experience. Combined with a low-band FDD 5G carrier, mid-band can provide full coverage and mobility. Good mid-band coverage is also essential for enabling differentiated connectivity and unlocking new revenue opportunities across consumer and enterprise use cases.

Large regional variations in 5G coverage By the end of 2025, 5G mid-band population coverage outside mainland China is projected to reach about 45%, but coverage levels vary significantly by region. Africa is expected to have the lowest total and mid-band 5G coverage, reaching about 10% by the end of 2025. The Middle East shows somewhat higher levels, with a total coverage of around 25% and mid-band coverage of about 20% expected.

Latin America, with 30% total and 25% mid-band 5G coverage, and Asia-Pacific (outside India and mainland China), with around 35% total and mid-band coverage, both remain below the global average for 5G population coverage. Extensive total and mid-band 5G coverage has been established across North America, mainland China and India, now covering 90-95% of the population in these regions.

Despite these coverage advancements, only around 35% of sites globally outside of mainland China have been upgraded to 5G mid-band.



**Figure 8.** World population and mid-band coverage split by region (end of 2025)

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## 5 Global momentum in commercial differentiated connectivity services

New offerings that leverage 5G standalone (SA) capabilities, such as network slicing, have progressed from limited pilots and niche experiments to fully launched commercial services. The ability for service providers to differentiate connectivity services – for example, by providing latency guarantees, priority services, security enhancements, immersive experiences, or connectivity targeting specific situations and locations or app categories – is changing with the introduction of 5G SA.

Market transitioning from proof-of-concept trials to commercial services that serve real customers in diverse contexts. This shift has been driven by advances in network capabilities and greater confidence among service providers, with an increasing willingness to explore new monetization models beyond traditional data and speed tiers. The extent of engagement is notable, with many service providers now active in several categories simultaneously.

This demonstrates scalability, market validation and confidence in the commercial viability of service offerings based on differentiated connectivity. Out of 118 such offerings, 55% are commercially available. Regional differences are notable, with unlimited offerings most prevalent in Western Europe, where about 86% of service providers include unlimited options in their plans.

There has been a constant growth in the number of service providers in recent years offering device-based plans, mainly driven by smartwatches. More service providers are deploying 5G networks that can support reduced capability (RedCap), and new categories of RedCap devices are expected to enter the market (beyond today's available broadband devices such as dongles and routers, surveillance cameras and smartwatches). Meanwhile, a range of new consumer and enterprise service offerings are expected to emerge.

Commercial broadband services using RedCap devices have been launched by one service provider in the US and by two service providers in the Asia-Pacific region.

Out of 79 service providers with commercially deployed 5G SA, there are 118 documented cases, from 56 service providers, of network slicing being used for some type of differentiated connectivity offering. Of these, 65 are commercially available either as a subscription service, an add-on package, or in the B2B and B2B2C space as a packaged, deployment-ready service. In the B2C sphere, application or situation-focused services such as video conferencing, gaming, event-specific packages and premium fixed wireless broadband subscriptions make up around 55% of all offerings.

In the B2B area, vertical markets like public safety, transport and logistics, defense and general enterprise use cases dominate.

In the parts of Europe where service providers have deployed 5G SA, they are increasingly active. The region accounts for 45% of all network slicing-related activities globally, including trials, proofs-of-concept and commercial offerings. Proportionally, there are more tests and trials in Europe than in other regions such as Asia-Pacific and North America. Out of all commercial offerings globally, 37 and 36% are in Europe and Asia-Pacific, respectively.

North America constitutes 18% of the offerings, with just one service provider accounting for three-quarters of all deployments in the region.

Learning to communicate benefits One recurring challenge identified by service providers, particularly in the consumer market, is how to explain new offers in terms that resonate with their customers. Selling “more gigabytes” or “faster speeds” is familiar territory – but telling the story of latency guarantees for gamers, uninterrupted HD streaming at live events, or priority service for emergency communications requires a more benefits-led approach. Customers respond more strongly when the offer is tied clearly to their personal experience, a specific app or situational need.

Speed, bandwidth, general performance or stability improvements are still being highlighted as user benefits in 86 of the cases based on network slicing. There are some new areas being highlighted, however, like latency (48%) or improved experiences when using a specific service or app (38%). In many cases, multiple benefits are communicated and combined to enhance the value proposition.

The number of service providers deploying 5G SA and starting to use network slicing to create differentiated connectivity offerings is increasing at pace. Meanwhile, service providers that were first to introduce differentiated connectivity, some as early as 2022, have now scaled up their deployments and started to broaden their reach. Across the 65 commercial offerings based on network slicing, half of them are offered by only six service providers. Of the network slicing use cases found, 65 are commercial offerings.

**Opportunities to offer tailored experiences**

Singapore is an island country, similar in size to New York City, with a population of around 6 million people. In 2022, with Singtel’s network buildout, it became the first country in the world to be fully covered (95 percent) by 5G SA. In 2025, the network was further enhanced with 5G low-band (700 MHz) added to the existing coverage. This delivers reliable nationwide coverage, especially improving deep indoor penetration. Singtel’s early-mover advantage has enabled it to explore and develop products and services to capitalize on the opportunities presented by 5G SA.

A business and technology journey Singtel’s early move into 5G SA clearly signals its strategic priorities. Service providers predominantly compete to offer data packages at the lowest price, meaning increasing the size of data buckets is no longer a differentiator in the hyper-competitive landscape.

Therefore, the top priority was to shift the conversation from data quantity to data differentiation, and to make enhanced experiences the new currency, where experience become the main measure of value. This was both a technical and marketing challenge, requiring a company-wide approach. Singtel’s strong belief that 5G SA is a strategic asset to achieve this goal has been a driving force behind its successful business transformation, embedding new ways of working to both maximize and commercialize the capabilities of 5G.

From a technology perspective, a robust and flexible network is required to support varying performance levels across consumer, enterprise and industry verticals. Key enablers such as network slicing, advanced traffic management and end-to-end quality assurance mechanisms mean Singtel can deliver consistent, predictable performance. Through the various capabilities unlocked in the network, they have been able to integrate with device and application ecosystems to ensure a seamless user experience.

Co-creation with partners, clear consumer monetization models and business outcome-driven offerings for enterprises are essential for success. Singtel was able to bring the technical and business aspects together through building a common language across the organization as a foundation, removing barriers between the technological and commercial sides of the organization. From here, a unifying goal of launching offerings that provided tailored experiences was built, based on the combined technical capabilities and value proposition of differentiated connectivity.

In 2022, Singtel had already achieved 95 percent nationwide 5G SA coverage.

	5G+	5G+ Enhanced	5G+ Priority
Connectivity	<b>Network PLUS – 700 MHz</b> <b>Coverage PLUS – deep inside</b>	<b>Network PLUS – 700 MHz</b> <b>Coverage PLUS – deep inside</b> <b>Enhanced network – 2x faster speed</b> <b>Enhanced roaming – trusted partners</b>	<b>Network PLUS – 700 MHz</b> <b>Coverage PLUS – deep inside</b> <b>Priority lane – 4x faster speed</b> <b>Priority roaming – first choice partners</b>
Services		<b>Enhanced security – security protection software</b> <b>Enhanced care – 24/7 hotline</b>	<b>Priority security – Mobile Protect</b> <b>Priority care – dedicated in-store service and 24/7 hotline</b>
Extras		<b>Enhanced deals – latest phones</b>	<b>Priority deals – 15 percent off accessories</b>

**Figure 16.** Singtel 5G+ commercial offerings structure

**6 Modernizing enterprise IT with 5G**

As digital transformation accelerates in the enterprise sector, service providers are well positioned to modernize enterprise IT, shifting from traditional site-bound perimeter models to secure, zero-trust endpoint-centric models that improve user experience while enabling agile, resilient operations.

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For decades, enterprise IT has largely revolved around centralized, site-based infrastructure. Data centers, on-premises servers and wired networks formed the backbone of corporate computing and communications. However, the rise of remote work, high-performing mobile networks and 5G laptops, and cloud services is disrupting this model. Enterprises now require greater agility, scalability and mobility to support distributed operations and real-time data processing.

The enterprise IT market encompasses a wide range of technologies and solutions designed to support complex business processes, enhance productivity, ensure security and enable digital transformation at scale. These technologies are typically implemented, managed and maintained by the enterprise's IT department. The trends of cloudification, hybrid working and AI are raising significant challenges for enterprises to cost-effectively and securely manage, maintain and develop existing IT infrastructure to meet future demands:

- **Cloudification:** The current software trends strongly lean toward cloud services driven by their flexibility, scalability, cost-effectiveness and ease of maintenance. As enterprise applications migrate to the cloud, IT infrastructure becomes lighter but also more distributed – requiring consistent management and security across locations and devices.

- **Hybrid working** has become the new normal for many organizations. Enterprises are now managing users and devices across office, home and mobile environments, requiring seamless and secure connectivity. This shift increases reliance on mobile networks and makes location-based security models less effective.

- **AI:** Enterprises are increasingly integrating AI tools into a wide range of business functions, and even moving beyond pilot initiatives to embed AI in their core operations, such as automating tasks and enabling real-time decision making. These applications depend on continuous, secure connectivity to access data and computing resources distributed between the cloud and edge. In this context, 5G's low-latency and always-on characteristics provide the foundation for secure and responsive AI-driven workflows, while also reinforcing the need for zero-trust security principles.

Enterprises face significant IT management challenges in: device selection, procurement and lifecycle management; network design and operations for both on-site and remote locations; and IT asset governance [10, 11].

The shift to hybrid work broadens the scope of these tasks. In environments that mix on-premises and cloud systems, secure operations based on zero-trust principles are increasingly essential. From a management perspective, the ongoing costs of maintaining legacy systems are a persistent concern.

**5G laptops:** Anywhere is a secure office Cellular-enabled laptop adoption is expected to grow faster than the overall laptop market. By 2030, the global installed base of 5G laptops is, by some external analysts, projected to approach 100 million, corresponding to a CAGR of approximately 45 percent between 2024 and 2030. The growth of 5G laptops, combined with the migration of enterprise applications to cloud platforms, serves as a catalyst for enterprise IT transformation.

This shift indicates that traditional perimeter-based, location-dependent enterprise IT network architectures will become increasingly obsolete, making way for more flexible, cloud-centric and zero-trust networking approaches enabled by seamless 5G connectivity both inside and outside the office.

Traditional, perimeter-based architectures rely on securing fixed physical sites and treating remote access as an exception – typically employing device certificates and virtual private networks (VPNs) to mimic a trusted internal environment. This approach is becoming less cost effective as modern workforces demand secure, seamless connectivity from anywhere, and as new operational models emerge that leverage 5G networks to meet evolving user demands and offer enhanced experiences.

A mobility-first, zero-trust network protects enterprise information assets by continuously validating both the user and the device, rather than basing security on physical location. Access rights are determined by identity and the device's security posture. By leveraging persistent device authentication based on non-removable eSIM and SIM credentials managed through the mobile network, and integrating these with enterprise-managed identity systems and device management platforms, organizations achieve a unified, high-assurance security framework that works seamlessly across office, home and mobile environments. With the traditional notion of a "secure location" disappearing, there is no longer a need to centralize assets at specific sites. This new model allows enterprises to provision, manage and secure devices anywhere – creating the foundation for more flexible operational practices.

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Service providers play a key role in enabling this transformation, as mobile networks provide the trusted, always-on connectivity required to verify users and devices continuously.

In a zero-trust environment built on persistent device identity, even traditionally IT-controlled tasks such as device provisioning can now be performed securely by end users. User-driven onboarding – supported by cloud-based Unified Endpoint Management (UEM) tools and integrated mobile authentication – enables employees to set up corporate devices directly, wherever they are, without compromising security. This approach reduces operational overhead and enhances flexibility in enterprise IT operations.

Cellular laptops maintain continuous connectivity via the mobile network. This ensures remote management functions and security actions can be immediately executed at any time and at any location, such as remote wiping or the removal of connection profiles if a device is lost or stolen. Always-on, network-native connectivity also gives IT administrators increased confidence in managing and responding to incidents by enabling consistent policy enforcement across all working environments within a zero-trust framework. While this consistent policy enforcement is a core benefit, another important advantage of cellular-first connectivity is the reduced dependence on extensive Wi-Fi infrastructure, enhancing both security and operational simplicity.

In collaboration with partners, SoftBank has been exploring new ways for enterprises to build secure and flexible connectivity for remote and hybrid workforces. High-performing 5G networks enable employees to securely access cloud-based services using 5G-connected laptops – whether in the office, at home or on the move. These initiatives illustrate how 5G connectivity can simplify enterprise IT architecture while supporting zero-trust and AI-enabled workflows that enhance both security and productivity.

In Japan, enterprises are increasingly looking for ways to improve both security and productivity through mobile-first IT environments. With cellular PCs providing continuous, secure connectivity within a zero-trust framework, this step was eliminated. Based on internal trials, this improvement translated into measurable productivity gains across the sales organization – the cumulative reduction is estimated to be up to one full working day per month, per employee. This demonstrates how cellular-enabled PCs can enhance both security and employee experience by enabling truly seamless, always-on access to enterprise resources.

As enterprises transition their office environments to support hybrid work and accelerate cloud migration, traditional LAN and WAN infrastructures often become underutilized yet still costly to maintain. According to Ericsson internal analysis, replacing parts of these conventional network environments with 5G-based architectures leveraging network virtualization could reduce overall IT infrastructure costs by up to 50%, depending on deployment conditions and enterprise size.

Ericsson Japan has also been implementing this approach within its own offices, gradually replacing local Wi-Fi environments with private 5G networks. Early internal results show reduced operational complexity and improved network reliability, providing a practical demonstration of how 5G can streamline enterprise IT and connectivity management. While the actual savings will vary, such 5G-enabled architectures offer opportunities to simplify network operations, improve agility and future-proof enterprise connectivity.

As enterprises accelerate cloud adoption and hybrid work, a fundamental shift from perimeter-based security to zero-trust models is becoming essential. A mobility-first, zero-trust architecture – powered by cellular-connected secure endpoints – enables service providers to deliver this transformation with capabilities unique to 5G mobile networks. This evolution not only strengthens enterprise security across all workspaces during hybrid working, but also streamlines operations and paves the way for more agile, flexible business practices by making 5G programmable networks available for enterprise IT.

Service providers are uniquely positioned to lead this transformation, integrating secure connectivity, identity management and managed lifecycle services into a cohesive solution offering for enterprise customers. In doing so, they enable enterprises to boost operational efficiency, strengthen security and reduce total cost of ownership (TCO) – while enhancing user experience and laying the groundwork for AI-driven innovation.

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The endpoint-centric model, powered by zero-trust, 5G and cloud technologies, is positioned to redefine enterprise IT architecture. Service providers who embrace this shift stand to gain not only new revenue streams but also deeper strategic partnerships with enterprises undergoing digital transformations.

***Video dominates downlink, but not uplink traffic***

Social platform video accounts for the vast majority of smartphone video viewing, while video-on-demand services deliver higher bitrates and superior quality of experience (QoE) scores. Comparing downlink and uplink traffic across four European mobile networks shows that video still dominates downlink usage, while cloud storage and communication services generate relatively more uplink traffic.

Video represents the largest portion of mobile data traffic across all four networks, accounting for around 50% of mobile traffic. Downlink traffic consistently shows a high share for video, reaching up to 60%. The share of video in uplink traffic, however, varies between networks. This variation reflects differences in user behavior, such as content creation and live streaming activity.

Communication services (including messaging, VoIP and video calls) are more bi-directional than video streaming, and therefore they generate a higher proportion of uplink traffic compared to downlink across the four sampled networks – 73% downlink and 27% uplink. The share of uplink traffic for communication services across the sampled networks ranges from 13 to 23%, while the share of downlink traffic remains around 5% or lower. This disparity underscores the interactive and user-driven nature of these services, where frequent user-originated activities such as voice and video calls, conferencing and content uploads significantly contribute to uplink traffic.

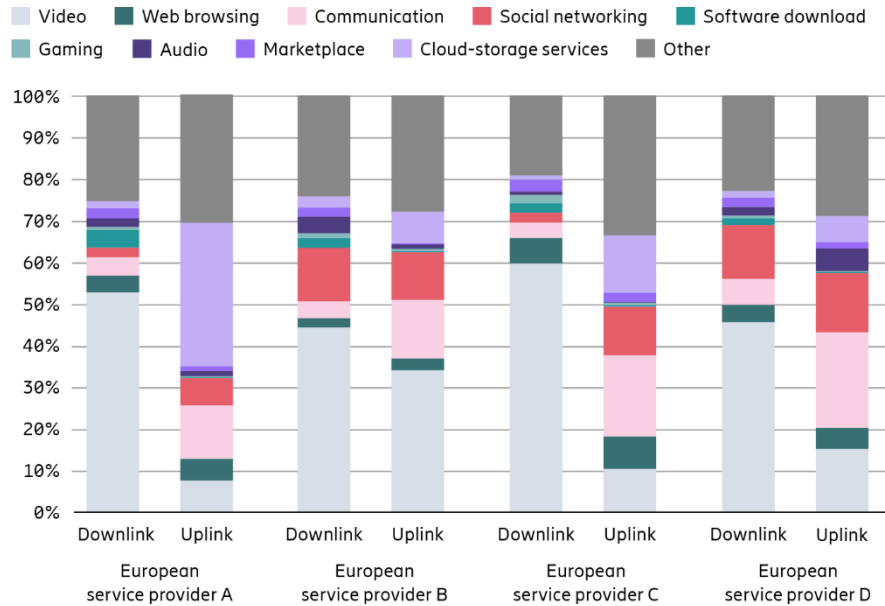
Across the sampled networks, social networking downlink traffic varies considerably, ranging from about 2 to 13%. For uplink, social networking usually ranks as the third-largest traffic category share – after video and either communications services or cloud storage – contributing roughly 7 to 14% of uplink traffic. Cloud storage services represent a substantially larger share of uplink traffic compared to downlink, highlighting active usage of cloud-based functions such as backups and file synchronization. Conversely, gaming, audio and software downloads consistently contribute less than 2% of both downlink and uplink traffic across all networks.

Across the four sampled European networks, a more detailed analysis of video traffic was performed, where video consumption of content from the most popular global service providers was grouped into two main categories:

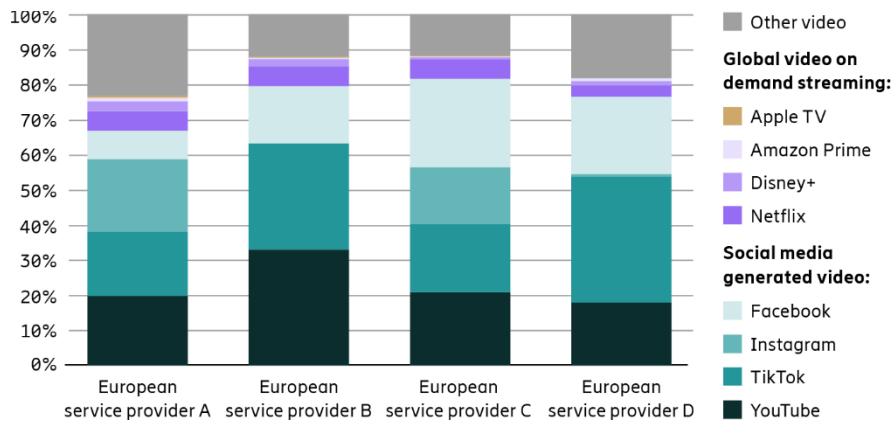
- social media-generated video (YouTube, TikTok, Instagram, Facebook);
- global video on-demand streaming (Netflix, Disney+, Amazon Prime, Apple TV).

The analysis shows that across the four European service providers, video traffic on smartphones is dominated by social media, far exceeding that of streaming video-on-demand services. For three of the service providers, social media video accounts for approximately 80% of all video traffic, while the fourth records nearly 70%. These results highlight smartphone users' clear preference for short, dynamic videos on social platforms.

Across the four European mobile service providers, YouTube consistently emerges as a leading video service by user share, with the share of mobile video users ranging from about 73% to nearly 99%. Almost every mobile video user consumes YouTube content, making it the dominant platform in terms of reach. In terms of traffic volume, it takes the clear lead in two networks with a 34 and 21% share, while in one network it shares the top position with Instagram, and in the fourth network it remains a major contributor despite a slightly lower user share.



**Figure 8.** Share of traffic volume in downlink and uplink per application category



**Figure 9.** Share of video traffic per video service provider

TikTok is the third most popular service by reach, with user share ranging from 52-59% and generating about 20–40% of the video traffic across the four service providers.

Instagram’s user base varies across the four networks: It engages around 50% of users in two networks, while its adoption remains limited in the other two. In terms of traffic share, Instagram is most dominant in one network, accounting for about 20% of the total traffic.

Facebook is especially popular in two networks, engaging more than 75 percent of video users and accounting for over 20% of total video traffic in both networks. Across the other networks, Facebook still attracts a large share of users, but it generates a smaller proportion of traffic there. This pattern suggests that consumption is driven by autoplay content and short-form formats like Reels, which increase user counts but have shorter viewing times.

Mobile video-on-demand’s role limited on smartphones Streaming of global video-on-demand services accounts for less than 10% of total mobile video traffic consumed on smartphones across all sampled networks. Netflix consistently dominates this category, contributing between 3 and 6% of total video traffic on these networks. Other services like Disney+, Amazon Prime and Apple TV+ have a relatively small share, typically less than

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1%. This limited usage on smartphones likely reflects users' preference to stream high-resolution content over Wi-Fi or fixed broadband connections and on larger devices such as tablets and PCs.

While traffic volumes and user behavior reveal a clear preference for short-form video content on social media platforms, the quality of the viewing experience is shaped by a range of technical factors. These include the capabilities of the smartphone itself, the encoding strategies of content providers and the performance of the underlying mobile network.

Mobile video experience on smartphones depends on several measurable factors, including intrinsic encoding quality (influenced by resolution, frame rate and codec) and dynamic quality effects such as time-to-content, rebuffering events and resolution adaptations to available channel capacity. It also depends on a specific smartphone model's capability. Calculated performance metrics across the sampled networks show that high-end flagship smartphones delivered the best streaming experience, with higher bitrates and QoE scores of above 4.2, while entry-level models showed lower bitrates and QoE scores of 3.6-4.0. Overall, flagship smartphones deliver a superior video streaming experience due to better bitrate performance and optimization.

As expected, professionally produced and optimized streaming services like Netflix and Amazon Prime deliver higher bitrates and superior QoE scores compared with social media video platforms. Notably, Instagram achieves unusually high QoE scores despite lower bitrates, suggesting particularly effective adaptation and encoding strategies that preserve perceived quality under constrained network conditions.

Across all four networks, 5G consistently delivers an improved video streaming experience compared with 4G. The enhancement is noticeable for long-form, high-quality content on video-on-demand platforms, where higher bitrates, shorter stall times and better QoE make streaming smoother. For short-form, social-media videos, 5G provides faster startup and smoother playback, minimizing interruptions as users rapidly scroll. In both cases, the upgrade to 5G results in a more responsive and reliable viewing experience.

## 7 Conclusion

The accelerated development and convergence of AI, cloud and mobile will fundamentally shift future traffic patterns, driving significant growth in uplink demands on mobile networks in the coming decade.

As intelligent devices increasingly rely on cloud-based processing, data is flowing in the uplink more than ever before. Yet, this shift is more complex than a simple surge in uplink demand. While AI-driven systems like AVs and AR glasses continuously send data to the cloud, advances in on-device intelligence, compression and smart data transport are reshaping how and when that data moves. The result is a more dynamic balance, where networks must support both the growing appetite for real-time cloud and the efficiencies that keep bandwidth use sustainable. Understanding this interplay is key to preparing for the next wave of connected intelligence.

The convergence of AI, cloud computing and mobile technologies represents one of the most transformative shifts in the digital era. Together, they create a powerful ecosystem where intelligence, scalability and accessibility reinforce each other: cloud platforms provide the computational infrastructure and storage capacity needed to deploy and train advanced AI models; mobile devices serve as both a data feed and the end-user interface to deliver these AI-powered cloud services, enabling personalized and context-aware experiences in real time; and networks provide ubiquitous and dependable connectivity between cloud and devices.

AI models hosted on the cloud can process massive datasets and deliver insights instantly to mobile users, whether they are powering smart assistants, enabling real-time language translation, or optimizing logistics and healthcare operations. Mobile devices therefore act not only as endpoints, but as data generators, feeding continuous streams of contextual information (such as location, behavior and sensor data) back to the cloud which, in turn, improves AI models through feedback loops.

As the convergence mentioned earlier happens, data rates increase further as a result. This will be particularly notable in the uplink. In the enterprise and industry sectors, for instance, 5G-native laptops, AI-enabled Internet of Things (IoT) devices, AVs, humanoid droids and drones will require significant uplink capacity. AVs and droids will transmit a lot of data to the cloud, as they collect a lot of training data, require data to be stored for legal reasons and sometimes require remote interventions. In the consumer

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space, personalized agents will be used on smartphones and emerging devices like AI and AR glasses, or similar companion devices. Some will be activated on demand, while other agents will be on all the time.

As a result, the uplink traffic will increase significantly over the coming years and, indeed, is becoming telecom's new "currency." Short term, this will be driven by the early adoption of AI glasses; mid term, by the adoption of AI assistants over AI/AR glasses at scale; and long term, by the large-scale deployment of AVs and possibly humanoid droids.

To effectively handle such an increase in uplink traffic, advancements such as carrier aggregation (CA) and Massive Multiple-Input Multiple-Output (M-MIMO) – available in 5G SA – enable more flexible and efficient use of spectrum across both frequency division duplex (FDD) and time division duplex (TDD) bands. For example, uplink traffic can be anchored on a low-band FDD carrier to maximize coverage and enhanced with FDD M-MIMO to boost capacity. Meanwhile, downlink capacity can be boosted through aggregation between FDD and a mid-band TDD carrier, leveraging TDD M-MIMO for higher throughput and improved overall performance.

Uplink requirements of current AI glasses to date, approximately 2 million smart glasses from leading manufacturers have been sold in the US – amounting to approximately 1 percent market penetration – with ambitions to sell millions per year going forward. The success driving these sales is in connecting the user to an AI agent that delivers sentient engagements based on video and audio input from the glasses.

Going forward, some models will use AI capabilities right on the glasses and/or tethered devices; however, advanced AI capabilities will need to run in the cloud and – when inference time of the models is low – the uplink network characteristics become critical. A recently announced smart glasses model has an advertised video capture resolution of 1,440 x 1,920 pixels. Multimodal AI on-demand engagements typically require framerates in the order of 5-10 frames per second (FPS) while being used. Always-on agents, on the other hand, are likely to use lower and perhaps dynamic framerates, such as 1 frame every 5-10 seconds.

The on-demand agent can make use of video codecs with a compression ratio of about 0.1 bits per pixel (bpp). At the given resolution and a frame rate of 5 FPS, this yields about 1.4 Mbps in the uplink. It is further assumed that for users of these AI agents, about 20% are "power users" at 100 min/day, with the remaining 80% being "ordinary users" at 10 min/day. This yields an average of 28 min/day.

The always-on agent will need to use image compression, at about 0.5 bpp; at the given resolution and a frame rate of about 0.1 FPS, this yields about 0.14 Mbps. It is then assumed that the agent is on for about 8h/day.

Resulting increase in the uplink percentage with regards to today's global average baseline of about 2 GB per month. Per user, the always-on agent consumes a slightly higher uplink than the on-demand agent under these assumptions. For a given device penetration, given the value on the x-axis in Figure 24, some users may adopt an always-on agent whilst others prefer on-demand. The future demand will therefore be between these two curves. This potential growth of uplink traffic underlines the importance of network capacity planning, spectrum allocation and RAN feature developments.

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