Assessing the Impact of Emerging Vertical Markets on 5G Diffusion Forecasting

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In this study, a methodology for overall 5G service diffusion forecasting is proposed that takes into account the introduction of 5G technology in multiple vertical markets. This methodology is based on stochastic modeling of 5G service diffusion in every vertical market under study.

Abstract

5G technology is not only a next-generation mobile network used for human communications, but also provides a worthy solution to machine-to-machine (M2M) communications requirements that contribute to the digital transformation of many vertical industries including factories of the future, media and entertainment, eHealth, and energy, among others. The assessment of the impact of 5G technology adoption by these M2M vertical markets on the overall 5G service demand represents a challenge for telecommunication operators, policy makers, and regulators, as it is a key factor affecting the underlying techno-economic analysis used for the formulation of their strategic planning and competition policy shaping. Within this scope, in this study, a methodology for overall 5G service diffusion forecasting is proposed that takes into account the introduction of 5G technology in multiple vertical markets. This methodology is based on stochastic modeling of 5G service diffusion in every vertical market under study. It also employs Monte Carlo simulation to generate potential forecast paths for the aggregate 5G service demand. Study findings indicate that the emergence of vertical markets has a significant positive impact on the saturation point of overall 5G demand without increasing the service's diffusion uncertainty to the same degree.

Motivation of the Study

The analysis of the diffusion patterns of telecommunication services (i.e., the number of devices utilizing a service) is a critical factor in determining the economic viability of these technologies. The generated knowledge is used by telecommunication service providers as a basis for strategic decision making regarding technology selection and capacity expansion, and by policy makers and regulators to shape market competition.

Previous generations of mobile networks — from 1G to 4G — aimed at satisfying human communications. These include voice and data services, accessed with hand-held or other portable electronic devices. Over time, the use of these technologies resulted in saturated markets, where telecommunication operators competed over a limited human subscriber base.

On the contrary, 5G technology, besides human communications, aims for industrial machine-to-machine (M2M) communications as well. It provides solid foundations to realize Internet of Things (IoT) applications: connected sensors to enable a smart city, connected robots for manufacturing plants, enhanced human mobility by connected cars and public transportation, and so on. Therefore, unlike previous mobile network technologies, 5G connected devices are expected to be utilized in other vertical markets as well, such as automotive, health, energy, media, manufacturing, and smart cities. These vertical markets might likely become the leading 5G adopters. These devices have different features and capabilities across different vertical markets.

For more information regarding the expected digital transformation, the impact of digital trends on business models of vertical industries, as well as the enabling technologies, like 5G, of this transformation, readers can find more information in [1], among other Industry 4.0 related literature. In this literature, the number and scale of vertical markets that are expected to adopt 5G technology largely depends on regional economic structure and technological readiness.

The importance that various organizations comprising the 5G ecosystem [2] attach to the diffusion of 5G technology in multiple vertical markets, termed 5G vertical markets, can be seen from the various initiatives undertaken to promote this diffusion, for example, the 5G Public Private Partnership (5G-PPP) Vertical Engagement Task Force (VTF) under the 5G Infrastructure Association (5G-IA). This interest closely relates to the significant financial impact (cash flows, profit margins, operating and maintenance costs, allocation of resources, expansion opportunities, inventory management, staffing, etc.) that the adoption of 5G in many vertical markets is expected to have on operators. It is expected that the introduction of 5G in multiple vertical markets will enable subscribers to expand their base beyond the demographic boundaries of the network deployment area, thereby generating higher profits, but it will also affect the diffusion process uncertainty, primarily due to each market's inherent diffusion uncertainty and the uncertain introduction date for 5G. Hence, to reduce risks and make efficient financial decisions, organizations need to formulate their strategic plans and policies based on accurate 5G diffusion forecasts. For example, the overall 5G demand forecast constitutes a key factor in the techno-economic analysis for an operator's 5G core network planning, radio access network (RAN) deployment, and network slicing planning.

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Despite the extensive literature related to telecommunication demand modeling and forecasting, to the authors' knowledge, no complete framework has been proposed to assess the impact of multiple vertical markets on the overall diffusion of an access service such as 5G. This constitutes a gap in the related literature.

Consequently, the purpose of this study is to propose a forecasting methodology for overall 5G service diffusion in a specific region. This methodology considers the introduction of 5G technology in multiple vertical markets, potential diffusion uncertainty parameters, and regional differences.

To assess the impact of the emergence of vertical markets on the overall 5G demand, in the proposed methodology, the overall 5G demand is considered an aggregate of each vertical market's 5G demand. The methodology begins with the identification and stochastic modeling of the diffusion process in each vertical market separately. The latter enables the incorporation of both positive and negative effects that the 5G diffusion process may exhibit due to competition from other M2M wireless technologies (WiFi, Bluetooth, 6LowPAN, ZigBee etc.) and consumer preferences. Monte Carlo simulation is then employed to capture the variable interactions of these markets through the generation of multiple possible aggregate future diffusion paths for the 5G service. This allows the generation of a risk-adjusted forecast of the overall 5G service demand.

This approach offers significant advantages over existing diffusion forecasting models that consider a single access technology market [3]. It captures the cumulative effect of the multiple vertical market growth trends in the 5G service's overall forecasted diffusion process. Furthermore, it provides a means to assess the impact that a specific vertical market has on overall 5G demand. These advantages constitute the novelty of the proposed methodology.

Furthermore, to date there is limited 5G diffusion data for most vertical markets. Thus, to shed light on the proposed methodology, an example application is presented. A telecommunications sector serving five different vertical markets, with uncertain 5G introduction time, is considered.

The rest of the article is structured as follows. A brief review of the literature on telecommunications demand modeling and forecasting is presented. An overview of the proposed 5G forecasting methodology is given. An illustration of how this methodology is applied is provided. Finally, we provide conclusions.

Brief Literature Review

According to [3, 4], telecommunications demand modeling and forecasting typically involves the use of traditional diffusion of innovations theory. Under this theory, the evolution of the demand for a specific product in a single market can be described by an S-shaped curve. In the telecommunications sector, the most used diffusion models include the Bass, Fisher–Pry, and Gompertz models and some representatives of logistic variants [3]. For 5G access technology, examples of this literature include the works of [5, 6].

The popularity of the aforementioned S-shaped diffusion models can be attributed to their effectiveness in capturing market expectations [3]. On the contrary, these models do not offer any ways to account for the inherent uncertainty in their projections [3]. As a result, the decision maker lacks the ability to evaluate and manage the diffusion-related risks that are present in the market under investigation.

To address this weakness, the literature suggests the use of stochastic modeling. In their attempt to model uncertainty, the authors of [7] proposed the contamination of data obtained from a known model-function by normally distributed errors. In [8, 9], geometric Brownian motion (GBM) is indicated as a mathematical tool that can be used for the calibration of demand volatility and as a first approximation of uncertainties. In [10], GBM with a linear growth rate is proposed for modeling a product's diffusion process over its life cycle. Reference [11] applied GBM modelling to generate future demand paths in the semiconductor manufacturing industry.

In the telecommunications sector, relevant literature is quite limited. In [12], GBM was used to analyze diffusion datasets from the telecommunication industry. More recently, in [13], a calibrated Ito stochastic process was used to generate future demand paths for a telecommunication service, thus allowing for the quantification of diffusion uncertainty in long-term diffusion forecasting.

The proposed methodology in this article builds on the work of [13]. It employs Monte Carlo simulation to highlight the effect that 5G adoption in multiple vertical markets has on overall 5G diffusion.

Formulation of the 5G Forecasting Methodology

In this section, the proposed 5G diffusion forecasting methodology is presented.

A vertical market is by definition made up of businesses that provide products and services to meet the demands of consumers in a particular industry or niche market. As a result, 5G solutions in a vertical market are tailored to the specific requirements of that market and typically do not serve a larger market.

Intuition suggests that the adoption of 5G in multiple vertical markets is beneficial for the overall diffusion of 5G technology. Each market has its own diffusion, in terms of connected devices, and the cumulative outcome is the aggregate overall 5G service demand.

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However, the adoption of 5G in multiple vertical markets also constitutes an additional source of diffusion uncertainty that needs to be managed. The latter is mainly attributed to the uncertainty inherent in each vertical market, as well as the uncertain 5G market deployment timing (a particular region may be technologically more ready to adapt a new capability than another).

In order to assess the cumulative impact of 5G adoption on overall 5G demand and at the same time quantify the resulting uncertainty, this study proposes a statistical and simulation-based methodology. This methodology consists of three steps:

1. The identification of 5G vertical markets
2. The stochastic modeling of the 5G diffusion process in each vertical market
3. The 5G service's diffusion forecasting through Monte Carlo simulation

The proposed vertical market stochastic modeling is being used to forecast future 5G demand. Furthermore, Monte Carlo simulation is used to

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quantify the uncertainty associated with cumulative 5G service diffusion.

To assess this uncertainty against the traditional human communications uncertainty, simulation outputs are compared with the equivalent results from the human market analysis. The latter consists of the base case application, for which 5G and previous mobile access technologies (1G to 4G), were intended.

Dentification of Vertical Markets

The first methodology implementation step consists of the identification of potential vertical markets. Various 5G vertical markets exist, with the most significant being automotive, transportation, media, smart city, healthcare, manufacturing, energy, public safety tourism, and agrifood.

Although it is expected that at some future point all vertical markets will be active in every geographical area, each practitioner may select some or all of them to perform the 5G technology diffusion forecast, based on information about the technological readiness for the area and the time period under study.

Stochastic Modeling of Vertical Markets

Having identified the 5G vertical markets, which are expected to affect the overall 5G service demand in the time period under study, to estimate the aggregate overall 5G service demand, the diffusion process underlying each vertical market is modeled separately.

The calibrated Ito stochastic process approach presented in [13] was chosen to model the 5G service diffusion process in a vertical market for the purposes of the proposed methodology. This model combines traditional diffusion theory with stochastic processes. It provides the practitioner with a lot of leeway in terms of process selection in order to accurately capture trends and uncertainty in the underlying diffusion processes.

The proposed calibrated Ito stochastic process is presented in Eq. 1:

$$dx = \mu(t)dt + b(x, t)dz \qquad (1)$$

where:

- dz is the increment of a Wiener process.
- The drift coefficient $\mu(t)$ corresponds to the calibrated diffusion growth rate, given by Eq. 2.

$$\mu(t) = \frac{\sum_0^t N(t) - \sum_0^{t-1} N(t-1)}{\sum_0^{t-1} N(t-1)} = \frac{N(t)}{\sum_0^{t-1} N(t-1)} \qquad (2)$$

- Shock coefficient $b(x, t)$ corresponds to a randomly scaled standard deviation of the modeling errors.

Equation 1 suggests that for each time step, a market's diffusion process will drift up by a timely variable drift rate $\mu(t)$. This drift rate is calculated from the best-fit curve function describing the market's diffusion growth with the use of Eq, 2, which presents a curve's typical growth rate calculation. To this drift is then added a random shock $b(x, t)dz$ (positive or negative) equal to the randomly scaled standard deviation of the modeling errors (i.e., the distance between the simulated and the actual market diffusion value). As a result, the diffusion proceeds in a series of steps, each of which consists of a drift plus or minus a random shock, which is a function of the standard deviation of the modeling errors.

The following points are highlighted:

1. Existing literature (e.g., [3]) suggests that telecommunication diffusion time series data present no seasonality or circularity. Thus, only trend and uncertainty parameters are examined.
2. The timely variable drift rate $\mu(t)$ is used to capture the trend of a vertical market's diffusion growth. This is calculated based on the best-fit function, as in Eq. 2. Thus, standard limitations of forecasting apply, including saturation level estimation, estimation window restrictions, and so on.
3. The shock parameter $b(x, t)$, which corresponds to the standard deviation of the S-curve modeling errors, combined with a Wiener process dz, is used to capture the uncertainty that 5G diffusion may exhibit throughout the technology's life cycle in a market. This uncertainty is due to various events (technological change, economic depression etc.) and is expressed as increased volatility of market diffusion data. When this parameter is used solely in diffusion modeling, it provides a measure of the market's inherent 5G diffusion uncertainty. On the other hand, when this parameter is examined under multiple path generation (Monte Carlo simulation) during diffusion forecasting, it enables the quantification of diffusion uncertainty and the associated risk assessment. Moreover, in the absence of diffusion uncertainty, the results of Eq. 1 converge to the best-fitting diffusion model to the market data.

For more information regarding the proposed calibrated Ito stochastic process and its use in telecommunications forecasting, one may refer to [13].

The use of the proposed stochastic process in Eq. 1 for each vertical market enables the utilization of different growth patterns, uncertainty quantification, and 5G diffusion saturation points. Moreover, if required, both positive and negative correlations between market diffusion processes may be implemented without affecting the methodology structure. For example, a standard bivariate normal distribution may be used to generate correlated market uncertainty data. Thus, the characteristics of each market's 5G-specific diffusion process, which contributes to the overall 5G service demand, are fully considered.

If required, or if new market data prove this approach to be incorrect (if diffusion data exhibit circularity and/or seasonality, etc.), different stochastic modeling may be used without affecting the methodology structure. This constitutes an extension of the proposed methodology.

Overall 5G Diffusion Forecasting

As mentioned, each vertical market exhibits its own 5G diffusion process. At any time step, overall 5G diffusion is equal to the sum of the 5G connected devices in each specific market.

As the 5G diffusion of the underlying markets was modeled according to a stochastic process in Eq. 1, Monte Carlo simulation can be used to generate multiple probable diffusion paths for each participating market separately. At any

Monte Carlo iteration and time step, the overall 5G demand is taken equal to the sum of the generated diffusion of all participating 5G vertical markets at that iteration and time step. Thus, multiple probable diffusion paths are also generated for the overall 5G service demand.

Furthermore, the introduction of 5G technology in different vertical markets may not be simultaneous. Some markets may be lagging, for example, due to a lack of technological readiness in the area under study. The proposed methodology should incorporate this time lag in the introduction of services, if any.

To address this problem, Monte Carlo simulation can also be used to generate randomly the introduction time of 5G service in a vertical market under consideration. This time indicates the time step from which the market's diffusion data will be taken into account in the overall 5G demand calculation. If a vertical market has not emerged at that time step, its demand is considered equal to 0. Therefore, at each time step, all identified/known vertical markets are addressed through the proposed methodology, even if they have not become active yet.

It is noted that if the diffusion process is studied under a Deming cycle, if new (unknown at an earlier time) vertical markets emerge, they can be incorporated into the analysis without affecting previous outputs.

At the end of the forecasting period, Monte Carlo simulation outputs a probability distribution of the expected overall 5G service demand, as well as for the participating markets' individual 5G demand at that time. Hence, the required risk-adjusted forecast of the overall diffusion process for the 5G service under study is provided.

M2M Vertical Market Impact Assessment

Unlike previous mobile network technologies, which were limited to human communications, 5G supports both human and M2M communications, opening up new markets.

To assess the impact of 5G M2M vertical markets on overall 5G demand, the overall 5G service risk-adjusted forecast is compared to the equivalent risk-adjusted forecast of the human market. The latter includes all 5G connected devices that support human communications only, forming common ground with previous mobile access technologies. This implies the comparison of two probabilistic distributions, which should be considered in terms of the minimum, maximum, mean, median, and standard deviation-variance values of the underlying distributions.

Example Methodology Application

In the absence of actual 5G M2M market diffusion data, to provide some more insight into the proposed methodology, an example case is presented in this section.

A telecommunications sector with the main human communications market and four M2M vertical markets (automotive, manufacturing, eHealth, and smart cities) is studied. The introduction of 5G technology in the additional vertical markets is expected to occur within the first 10 years, following the introduction of the same technology in the human market. The impact of the uncertainty introduced by vertical markets is assessed at the end of a 15-year period, which constitutes the forecast target time.

Market	S-curve model	Saturation parameter S	Parameter a	Parameter b	Shock coefficient $b(x, t)$
Human	Logistic	12,036,363	0.621	8.051	0.07
Automotive	Logistic	5,246,713	0.561	9.765	0.05
Manufacturing	Logistic	502,489	0.764	7.89	0.08
eHealth	Logistic	26,035	0.235	5.674	0.05
Smart city	Logistic	5,365,897	0.643	7.743	0.09

TABLE 1. 5G market-specific diffusion modeling.

Modeling of the Participating Vertical Markets

Following the proposed methodology, for the five given 5G vertical markets of interest (human, automotive, manufacturing, eHealth, and smart cities), the calibrated Ito stochastic process (Eq. 1) is utilized to describe the demand evolution of 5G service for each participating market.

For simplicity, a logistic growth model is considered (best-fit curve model) for all markets, described in (3),

$$f(t) = S/(1 + b \cdot e^{-a \cdot t}) \quad (3)$$

where:
- $f(t)$ is the calculated diffusion at time t.
- Saturation parameter S corresponds to maximum forecasted diffusion value.
- Growth coefficients a and b correspond to parameters affecting the growth rate (steepness of the curve).

The used diffusion stochastic modeling parameters were chosen arbitrarily. These parameters are presented in Table 1.

It is noted that the modeling parameters in Table 1 have been selected so that each vertical market is modeled to follow a different diffusion pattern, resulting in different uncertainty impacts on the overall 5G demand.

Monte Carlo Simulation Application

Based on the proposed methodology, to generate the required probabilistic distribution of the overall 5G service demand at the end of the 15-year period, Monte Carlo simulation is used. 15 time steps were defined, each representing a simulation year.

For every time step and Monte Carlo iteration, each market's demand is calculated following the stochastic modeling of Table 1.

To model each market's 5G launch uncertainty, this time was allowed to vary randomly for each simulation iteration between 1 and 10 years. This implies that 5G may be adopted by each vertical market at random over a 10-year period. The market's diffusion growth was then shifted to match the simulated introduction time.

It is noted that a practitioner may use different time frames for the introduction of each vertical market under study. This also includes time periods starting from time steps other than 1 (e.g., 2–5).

Finally, the overall 5G service demand was assumed to be equal to the sum of the individual vertical market diffusion estimates at each time step and Monte Carlo iteration.

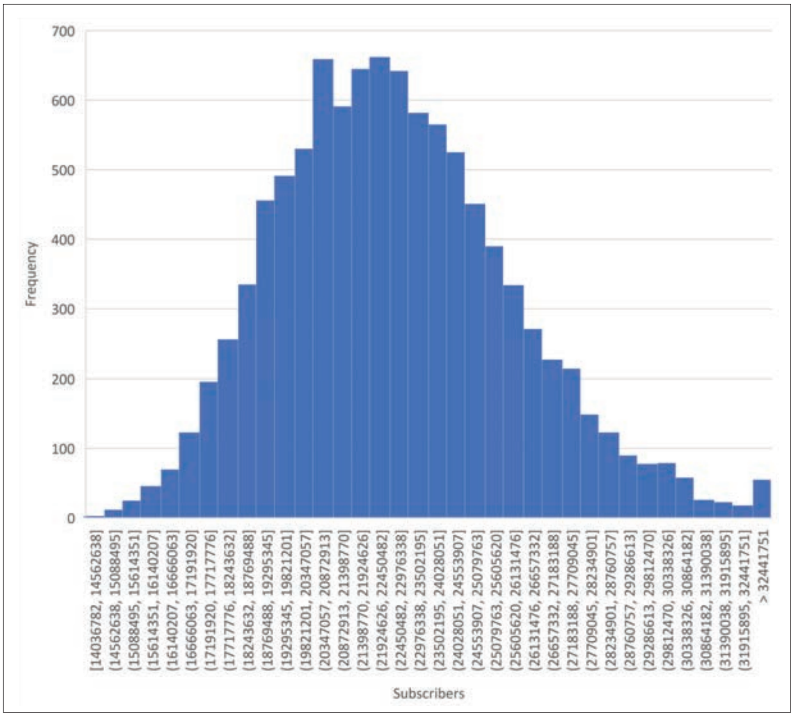

FIGURE 1. Overall 5G risk-adjusted diffusion forecast.

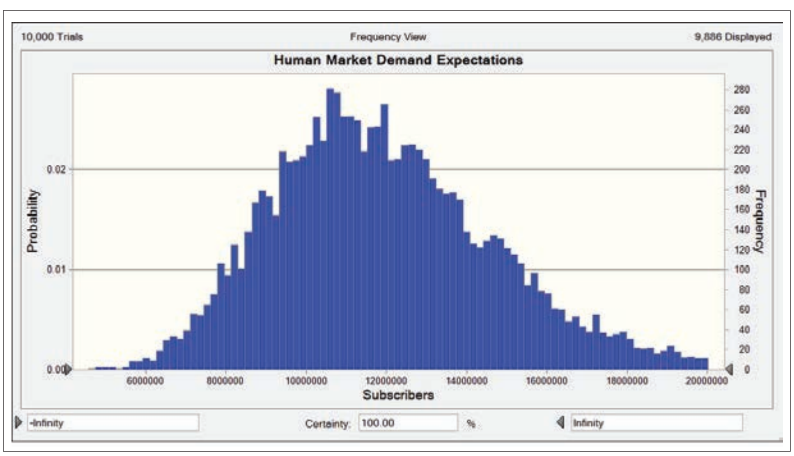

FIGURE 2. Risk-adjusted human market 5G diffusion forecast.

Given the above, simulation outputs, the probability distribution of the overall 5G diffusion process at the end of the 15-year period, which serve as the foundation for equivalent risk assessment, are shown in Fig. 1.

Among others, the risk assessment of the results, presented in Fig. 1, suggests that the overall 5G demand is expected to fall within the region [(18,275,782), (24,636,782)]; more than 50 percent of the simulation results are within this region. Moreover, there is a 50 percent chance that the overall 5G demand will not exceed 23,000,000 connected devices.

M2M Vertical Market Impact Assessment Results

To assess the impact of 5G M2M vertical markets on the overall 5G diffusion forecast, the risk-adjusted 5G forecast for the overall telecommunications sector, presented in Fig. 1, is compared to the equivalent human market forecast for the same time period. The risk-adjusted human market forecast is presented in Fig. 2.

According to Fig. 2, the human market presents significantly lower expectations, with 50 percent of simulation results being in the region between 10 and 12.5 million connected subscribers. As predicted, the adoption of 5G in multiple vertical markets can have a significant impact on overall 5G demand as a positive speed of adoption is observed.

To provide some more insight into the assessment results, the statistics of the probability distributions compared above (Figs. 1 and 2) are examined. These are summarized in Table 1.

As shown in Table 2, the existence of vertical markets almost doubles the mean and median values of the telecommunication sector's expectations of overall 5G service demand. In addition, the minimum expected value of total sector diffusion is higher than the mean and median value of human market expectations. Therefore, there is a significant positive effect of the four modeled vertical markets on the overall 5G demand saturation point, and hence on 5G service market performance.

Furthermore, the standard deviation of the forecasted diffusion (simulation results) increases by almost 14 percent. This increase indicates a more volatile and therefore more uncertain market. However, this increase is proportionally smaller than the increase in the overall demand saturation point. This indicates that the existence of multiple vertical markets negates most of the negative effects on demand attributed to each participating market's uncertainty.

The above findings suggest that the addition of new M2M vertical markets achieves a six-fold higher diffusion-to-risk ratio. Therefore, a successful 5G monetization strategy might lead to an increase in market size with low risk.

Limitations of the Work

As already mentioned, this study is subject to limited actual market data and a lack of previous research studies on the topic. This is because 5G investments in most M2M markets have been limited to pilot projects and have not yet progressed to full-scale deployment. As a result, the specific characteristics of each potential 5G vertical market's diffusion process are unknown.

As a result, the following market assumptions regarding the 5G diffusion process in each vertical market were used in the example 5G diffusion forecasting application:

1. M2M market diffusion exhibits a typical S-curve growth pattern, similar to traditional human communication markets [3]. In the absence of other evidence, this assumption was made for M2M markets to support the traditional diffusion of innovations theory.
2. For simplicity, vertical markets are assumed to be independent. No correlation is considered between the 5G diffusion process exhibited by different vertical markets.

Moreover, no validation of the methodology, based on actual market data, is provided. This is left for future work when sufficient market data are available.

Conclusions and Future Research Work

Novel 5G communication technology, which aims at the digitization of the economy, is expected to expand its diffusion beyond the traditional human subscriber base to other vertical industries.

To address the overall 5G diffusion forecasting problem, in this study, a methodology based on stochastic demand modeling and Monte Carlo simulation is presented. The proposed methodology estimates the impact of 5G technology introduction on multiple vertical markets on the overall diffusion of 5G technology. Its flexibility allows the inclusion of market function changes that may occur following the arrival of actual market data.

In light of the work limitations provided, an example application indicates that the emergence of 5G vertical markets can have a significant positive impact on the saturation point of overall 5G demand without increasing the overall telecommunication sector's 5G diffusion uncertainty.

Future work includes the extension of the proposed methodology to include additional market uncertainty functions and/or market characteristics, the validation of the methodology using actual market data, and its application to other IoT-enabling technologies, provided that they allow the emergence of vertical markets.

Statistic	5G demand stemming from human market only	Overall 5G demand stemming from all active vertical markets
Trials	10,000	
Mean	12,003,877	22,632,193
Median	11,694,843	22,370,558
Standard deviation	2,864,387	3,269,853
Skewness	0.6504	0.5214
Kurtosis	3.62	0.443
Minimum	4,566,299	14,036,782
Maximum	26,560,441	40,579,110
Mean std. error	28,644	32,699

TABLE 2. Comparison of 5G diffusion forecasts.

References

[1] L. Banda, M. Mzyece, and F. Mekuria, "5G Business Models for Mobile Network Operators — A Survey," *IEEE Access*, vol. 10, 2022, pp. 94,851–86. DOI: 10.1109/ACCESS.2022.3205011.

[2] H. K. Hallingby *et al.*, "5G Ecosystems," *Zenodo*, 2021. DOI: 10.5281/zenodo.5094340.

[3] N. Meade and T. Islam, "Forecasting in Telecommunications and ICT — A Review," *Int'l. J. Forecasting,* vol. 31, no. 4, 2015, pp. 1105–26. DOI: 10.1016/j.ijforecast.2014.09.003.

[4] R. Fildes and V. Kumar, "Telecommunications Demand Forecasting — A Review," *Int'l. J. Forecasting,* vol. 18, no. 4, 2002, pp. 489–522. DOI: 10.1016/S0169-2070(02)00064-X.

[5] A. Jha and S. Debashis, "Diffusion and Forecast of Mobile Service Generations in Germany, UK, France and Italy — A Comparative Analysis Based on Bass, Gompertz and Simple Logistic Growth Models," *26th Euro. Conf. Info. Systems: Beyond Digitization — Facets of Socio-Technical Change*, 2018.

[6] G. Smail and J. Weijia, "Techno-Economic Analysis and Prediction for the Deployment of 5G Mobile Network," *20th IEEE Conf. Innovations in Clouds, Internet and Networks*, 2017. DOI: 10.1109/ICIN.2017.7899243.

[7] R. Scitovski and M. Meler, "Solving Parameter Estimation Problem in New Product Diffusion Models," *Applied Mathematics and Computation,* vol. 127, no. 1, 2002, pp. 45–63. DOI:10.1016/S0096-3003(00)00164-8.

[8] Y. C. Chou *et al.*, "Evaluating Alternative Capacity Strategies in Semiconductor Manufacturing Under Uncertain Demand and Price Scenarios," *Int'l. J. Production Economics*, vol. 105, no. 2, 2007, pp. 591–606. DOI: 10.1016/j.ijpe.2006.05.006.

[9] T. Yao *et al.*, "Outsourcing Timing, Contract Selection, and Negotiation," *Int'l. J. Production Research*, vol. 48, no. 2, 2010, pp. 305–26. DOI:10.1080/00207540903174858.

[10] R. Qin and D. A. Nembhard, "Demand Modeling of Stochastic Product Diffusion Over the Life Cycle," *Int'l. J. Production Economics* vol. 137, no. 2, 2012, pp. 201–10. DOI:10.1016/j.ijpe.2012.01.027.

[11] Y. C. Chou *et al.*, "A Comparative Study on the Performance of Timing and Sizing Models of Capacity Expansion under Volatile Demand Growth and Finite Equipment Lifetime." *Computers & Industrial Engineering 76*, 2014, pp. 98–108. DOI:10.1016/j.cie.2014.07.027.

[12] R. R. Marathe and S. M. Ryan, "On the Validity of the Geometric Brownian Motion Assumption," *The Engineering Economist*, vol. 50, no. 2, 2005, pp. 159–92. DOI: 10.1080/00137910590949904.

[13] N. Kanellos, D. Katsianis, and D. Varoutas, "On the Introduction of Diffusion Uncertainty in Telecommunications' Market Forecasting," *Engineering Proceedings*, vol. 5, no. 1, 2021, p. 13. DOI: 10.3390/engproc2021005013.

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