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Growth of Digital Infrastructure of China and USA: Application of Intelligent Grey Forecasting Model

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Abstract: Mobile cellular telephone subscriptions and secure internet servers play an important role in the digital infrastructure of the country, and their growth projections hold useful information for planners and policymakers. The current study makes a pioneering attempt to forecast the growth in mobile cellular subscriptions and secure internet servers in the United States of America and China using an intelligent and flexible time-series grey model called EGM (1,1, α, θ). Secure internet servers in the US and China are projected to grow exponentially, while mobile cellular subscriptions for both countries showed linear growth. The error analysis done through the mean absolute percentage error revealed some interesting results related to secure Internet servers. The results provide useful insights for proper planning of the digital infrastructure of the two digital powerhouses.

Keywords: Grey forecast; time series forecasting; mobile cellular telephone subscriptions; secure internet servers

1. Introduction

In today's digital world, the number of mobile cellular subscriptions and secure internet servers are key indicators of a country's technological growth and economic competitiveness (Lee *et al.*, 2021). Secure internet servers are web servers that encrypt data transfers using SSL/TLS protocols. To use cellular technology for internet access and mobile telephones, one must first subscribe to a public mobile network. In 2020, the World Bank recognized secure servers and mobile subscribers as two indicators of a country's Internet infrastructure, connectivity, and preparation for 5G and Internet of Things (IoT). China's investments in digital infrastructure, including Made in China 2025 and Digital Silk Road, have established the country as a technical powerhouse (Chan, 2022).

By promoting economic growth and worldwide competitiveness, these initiatives help the organization achieve its goal of improving cybersecurity techniques and making its services more accessible to the general public. To remain competitive, the United States of America, long regarded as a technical innovation leader, is focusing on developing a safe digital economy that encourages better connectivity while implementing rigorous cybersecurity measures (Erondu & Erondu, 2023). Both countries are at the vanguard of digital transformation and their examples serve as models for how other countries might develop their technological capabilities. Digitalization in China and America are vital to the global economy that is closely intervened in these two major economies through their trade relations. It includes growing secure internet servers in China, which demonstrates how quickly it can tackle any cybersecurity challenges and improve its status in technology (Bauer & Dutton, 2015). Likewise, the increase in mobile cellular subscribers reveals how far a country has progressed in terms of bridging urban-rural divides in digital connectivity (Wang *et al.*, 2021). The growth in cellular subscriptions also emphasize the need to safeguard key industries, such as finance, healthcare, and e-commerce, from cyber threats (Luo & Choi, 2022; Desamsetti, 2021).

The mobile market of the United States may be mature, but seedlings of incremental advancement through IoT and 5G technologies continue planting so that the country stays ahead in telecommunication innovation (Tom, 2023). Thus, getting to know all of these trajectories is paramount, since this comes ahead of any other development that would set global benchmarks for technological innovation and economic progress. The focus on secure internet servers and mobile cellular subscriptions as primary variables is not arbitrary. These indicators encapsulate the crux of digital infrastructure and connectivity, which are essential for economic growth and innovation. China has the potential to scale its digital infrastructure swiftly beyond the former model and would, therefore, offer lessons to developing countries aspiring not just to catch up but, more importantly, to leapfrog their technological power (Hu *et al.*, 2023). In contrast, the US approach, which focuses on quality, safety, and sustainability, can be a roadmap for many countries with a well-established digital marketplace while attempting to remain competitive (Mueller & Farhat, 2023). Most countries are rapidly catching up in digitalization, all but one: no other place has the global influence and transformation potential of either China or the US.

The aim of this study was to forecast the growth of secure internet servers and mobile cellular subscriptions in China and the US using the EGM (1,1, α, θ) model for 2024-2033. The rest of the study is organized as follows. After the introduction section, the methodology section is presented. In this section variables, data, the forecasting model, and forecast accuracy measurement methods are discussed. In the next section, results and discussions are presented. In the last section, conclusions and limitations are given.

2. METHODOLOGY

2.1 Variables and data

The study forecasted two variables; Secure internet servers and, mobile cellular telephone subscriptions. Secure internet servers are "the number of distinct, publicly-trusted TLS/SSL certificates found in the Netcraft Secure Server Survey" (World Bank, 2024a). It refers to the total secure servers of a country, which indicates the amount of effort that a country has put into servicing its cyberspace and securing commerce and communication. Meanwhile, mobile cellular subscriptions are "subscriptions to a public mobile telephone service that provide access to the PSTN using cellular technology" (World Bank, 2024b). It indicates the number of active cellular mobile subscriptions reported within the boundaries of each country to determine the extent of mobility and telecommunication technology employed. Data from 2015 to 2023 was collected from World Bank (2024a; 2024b).

2.2 The forecasting technique

Grey System Theory is an emerging field of artificial intelligence and data science. Grey forecasting models (Podrecca & Sartor, 2023), grey numbers (Voskoglou, 2023), grey relational analysis models (Nawaz *et al.*, 2024; Nawaz *et al.*, 2022) form the core tenants of the theory. What distinguishes the grey forecasting models from statistical forecasting techniques is its data processing procedures and time-response functions (Javed & Cudjoe, 2022). The current study used an advanced grey forecasting model called EGM (1, 1, α, θ) that was proposed by Javed *et al.* (2020). It is a generalized form of the classical even grey model EGM (1, 1) and reduces to its original form when α = 1 and θ = 0.5. The advanced model is more flexible and can adapt to nonlinear time series data as well. Let the actual data set is

$$X^{(0)} = \left(x^{(0)}(1), x^{(0)}(2), \dots x^{(0)}(n)\right)$$

If we aggregate it using $x^{(1)}(k) = \sum_{j=1}^{k} x^{(0)}(i)\,, k = 1,2, \dots, n$ it becomes,

$$X^{(1)} = \left(x^{(1)}(1), x^{(1)}(2), \dots x^{(1)}(n)\right)$$

Later, with the help of $z^{(1)}(k) = \theta.\, x^{(1)}(k) + (1 + \theta).\, x^{(\alpha)}(k-1)$ the following data set is estimated,

$$Z^{(1)} = \left(z^{(1)}(1), z^{(1)}(2), \dots z^{(1)}(n)\right)$$

The model's continuous-time grey differential equation is defined as

$$\frac{dx^{(1)}(k)}{dk} + ax^{(1)}(k) = b$$

which is approximately equivalent to

$$x^{(0)}(k) + az^{(1)}(k) = b$$

Later, the least square approach is used to calculate the parameters a and b, i.e.

$$[a, b]^T = [B^T B]^{-1} B^T Y$$

where,

$$B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(i)}(n) & 1 \end{bmatrix} \text{ and } Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix}$$

The time response function of the model is

$$\hat{x}^{(\alpha)}(k) = \left(x^{(0)}(1) - \frac{b}{a}\right) e^{-a(k-1)} + \frac{b}{a}, k = 1,2, \dots, n$$

To extract simulation of the actual data the following equation will be used,

$$\hat{x}^{(0)}(k) = k^{1-\alpha}\left(\hat{x}^{(\alpha)}(k) - \hat{x}^{(\alpha)}(k-1)\right), k = 1,2, \dots, n;\ \hat{x}^{(0)}(0) = 0$$

And the time-response expression of the actual data $X^{(0)}$ is given as

$$\hat{x}^{(0)}(k) = k^{1-\alpha}(k - e^{\alpha})\left(x^{(0)}(1) - \frac{b}{a}\right) e^{-\alpha(k-1)}, k = 1,2, \dots, n$$

The current study used the optimization technique proposed by Javed *et al.* (2020) to estimate the values of α and θ.

2.3 Forecast error measurement

The Mean Absolute Percent Error (MAPE) is an effective measure for calculating forecast error, and is given as follows (Javed & Cudjoe, 2020),

$$MAPE(\%) = \frac{1}{n} \times \sum_{k=1}^{n} \left| \frac{x(k) - \hat{x}(k)}{x(k)} \right| \times 100$$

where $x(k)$ and $\hat{x}(k)$ are indicative of both observe and simulate (forecast) values obtained through the model. According to the Javed-Cudjoe scale, a $MAPE$ (%) of less than 20% reflects a good prediction (Javed and Cudjoe, 2020):

$$\text{MAPE}(\%) = \begin{cases} < 10 & Highly\ accurate\ forecast \\ 10\sim20 & Good\ forecast \\ 20\sim30 & Reasonable\ forecast \\ > 30 & Inaccurate\ forecast \end{cases}$$

3. RESULTS AND DISCUSSION

Tables 1 and 2 comprise two sections, where the first section belongs to secure internet servers and the second section belongs to mobile cellular subscriptions. The first column in both tables

Table 1. Forecasting China's secure internet servers and mobile cellular subscriptions

	Secure internet servers (Thousand)			*Mobile cellular subscriptions (Million)*		
	Actual Data	*EGM (1,1, a, θ)*	*MAPE (%)*	*Actual Data*	*EGM (1,1, a, θ)*	*MAPE (%)*
2015	27	27		1290	1290	
2016	66	398	503.0	1360	1451	6.7
2017	290	519	79.0	1470	1504	2.3
2018	622	673	8.2	1650	1558	5.6
2019	1027	870	15.3	1750	1614	7.8
2020	1338	1122	16.1	1720	1671	2.8
2021	1531	1445	5.6	1730	1730	0.0
2022	1860	1860	0.0	1770	1791	1.2
2023	2128	2392	12.4	1810	1854	2.4
2024		3074			1919	
2025		3949			1986	
2026		5070			2055	
2027		6508			2127	
2028		8351			2201	
2029		10713			2277	
2030		13740			2357	
2031		17620			2439	
2032		22591			2523	
2033		28960			2611	
a		-0.245704			-0.033873	
b		0.332756			1373.698	
α		0.951069			0.993344	
θ		1			1	
MAPE (%)			79.9			3.58

Table 2. Forecasting the US secure internet servers and mobile cellular subscriptions

	Secure Internet servers (Thousand)			*Mobile cellular subscriptions (Million)*		
	Actual Data	*EGM (1,1, a, θ)*	*MAPE (%)*	*Actual Data*	*EGM (1,1, a, θ)*	*MAPE (%)*
2015	2.04	2.04		332	332	
2016	3.69	15.26	313.6	338	335	0.9
2017	9.86	18.72	89.9	340	341	0.3
2018	21.52	22.94	6.6	348	347	0.3
2019	40.71	28.08	31.0	356	353	0.8
2020	46.68	34.36	26.4	353	360	2.0
2021	52.12	42.04	19.3	362	366	1.1
2022	60.19	51.42	14.6	373	373	0.0
2023	62.88	62.88	0.0	386	380	1.6
2024		76.89			387	
2025		94			394	
2026		114.92			401	
2027		140.48			408	
2028		171.72			416	
2029		209.89			423	
2030		256.53			431	
2031		313.53			439	
2032		383.17			447	
2033		468.27			455	
a		-0.200001			-0.018121	
b		13.28111			325.5348	
α		0.989555			1	
θ		1			0.528325	
MAPE (%)			62.7			0.87

represents the time series from 2015 to 2023. Four parameters (a, b, α, and θ) are also shown in the same column. The actual data of the servers in thousands are presented in second columns. The simulation of the actual data and its forecast are presented in the third column. The simulations were performed using the EGM (1, 1, α, θ) model. The fourth column contains the MAPE values.

In the tables, the first column of the second section is the actual data of the subscriptions in millions, and the next two columns are the simulations obtained through the grey forecasting model and MAPE values. The first section of Table 1 presents the analysis of servers, where China is projected to grow to 28,960 thousand secure internet servers by 2033 which was 27 thousand in 2015 and 2128 thousand in 2023. This trend is exponential, as shown in Figure 1.

The second section of Table 1 presents an analysis of the subscriptions, where China is projected to grow to 2,611 million mobile cellular subscriptions by 2033 which was 1290 million in 2015 and 1810 million in 2023. The trend is linear, as shown in Figure 2. The findings indicate that China aims to bolster its stance towards better digital security; thus, its focus on secure Internet servers and mobile cellular subscriptions is likely to sustain long-term growth in the long run.

As discussed earlier, Table 2 also comprises two sections, where section 1 belongs to secure internet servers and section 2 belongs to mobile cellular subscriptions in the US. The first section of Table 2 presents the analysis of the servers, where the US is projected to grow to 468.27 thousand secure internet servers by 2033 which was 2.04 thousand in 2015 and 62.88 thousand in 2023. The trend is linear, as shown in Figure 3.

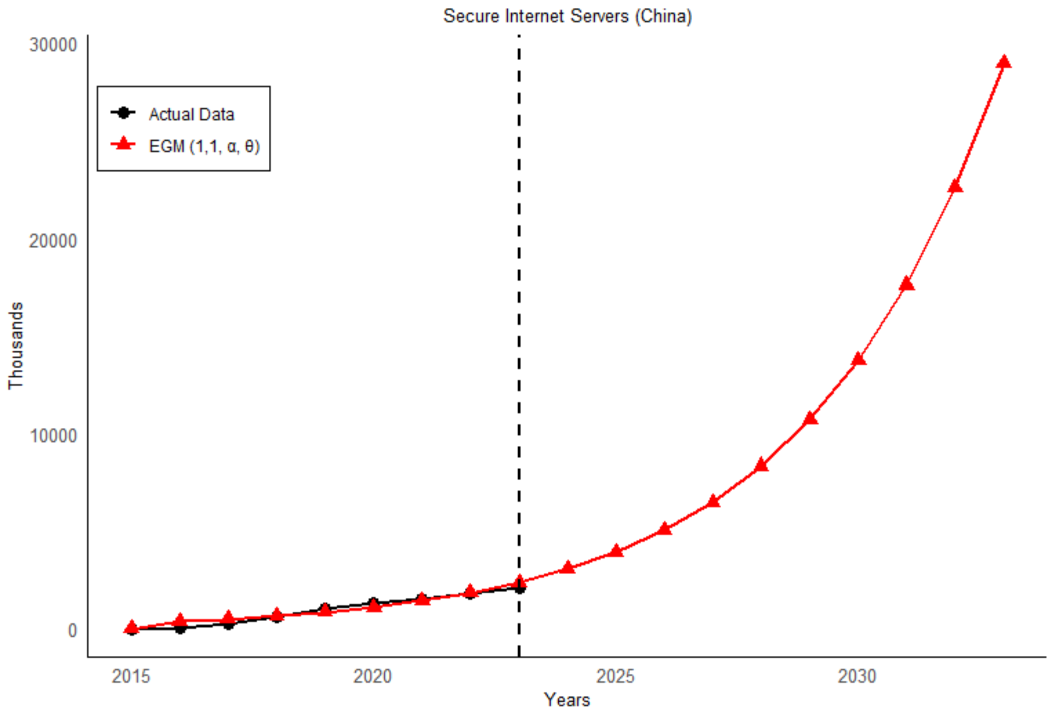

Figure 1. China's secure internet servers

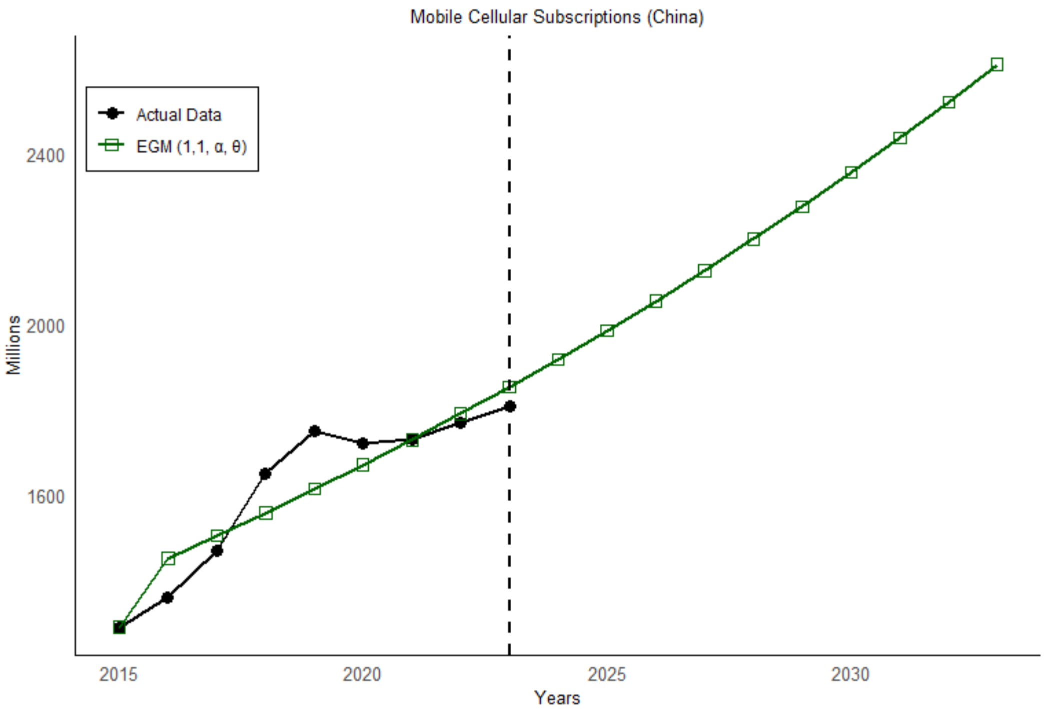

Figure 2. China's mobile cellular subscriptions

The analysis of the second section of Table 2 reveals that the US is projected to grow to 455 million mobile cellular subscriptions by 2033, which were 332 million in 2015 and 386 million in 2023. The trend is linear, as shown in Figure 4. The findings indicate that the US focused on enhancing cybersecurity, strengthening its digital economy, and substantial growth in secure servers. The trajectories of both countries underscore the critical role of digital infrastructure in shaping their economic and global competitiveness.

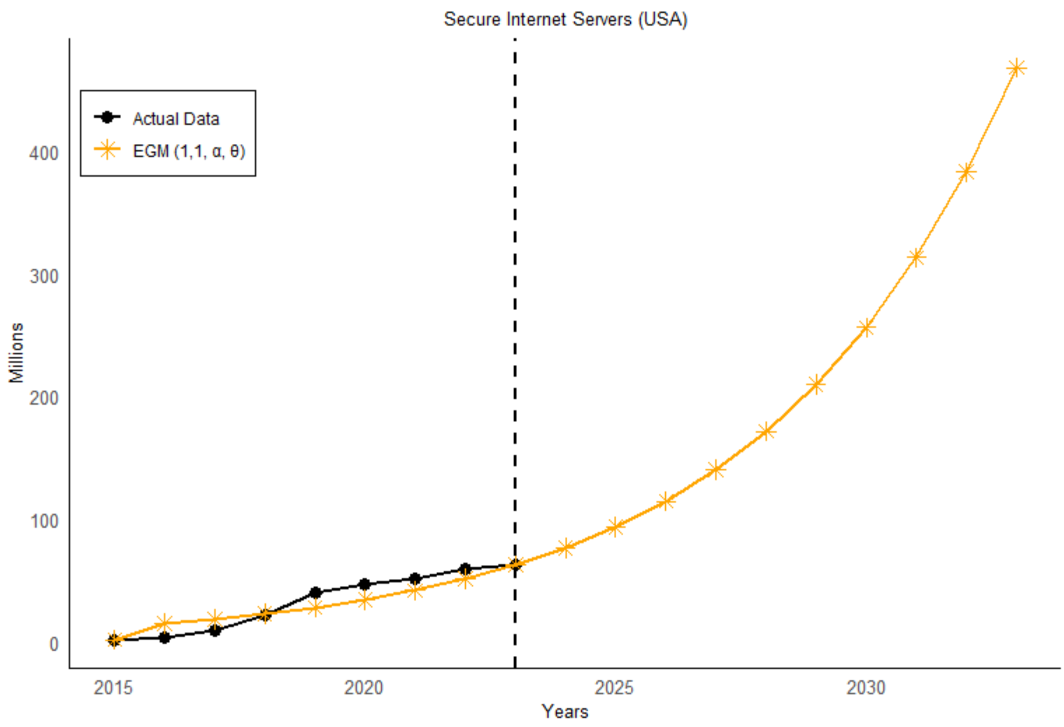

Figure 3. The USA's secure internet servers

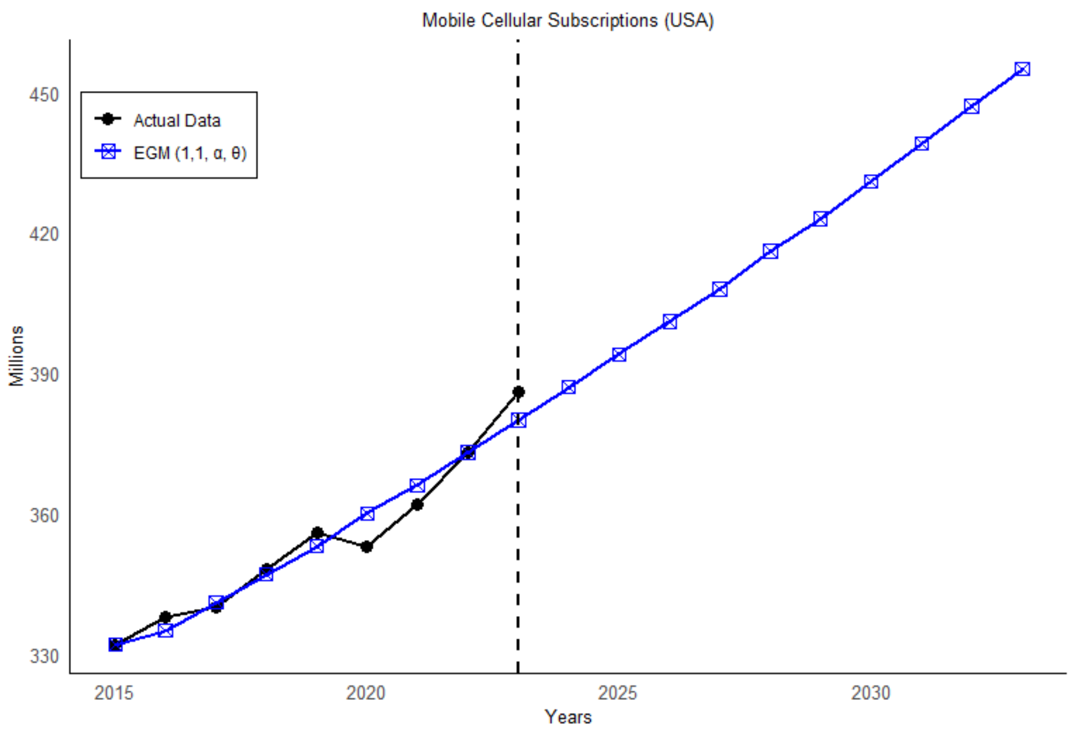

Figure 4. The USA's mobile cellular subscriptions

Technological advancement and infrastructural development have emerged as central pillars for all nations looking for a competitive edge in the global stage, as well as economic sustainability. In the mechanical era, countries that focus on the provision of secure internet servers and mobile connectivity have a clear edge in terms of productivity and intellectual power (Weiss, 2021; Liu *et al.*, 2022; Xiao *et al.*, 2022; Xiaobo *et al.*, 2023; Rosenberg *et al.*, 1992). With secure internet servers being an important aspect of cyber security and building trust in the digital world, mobile cellular networks are the second most important aspect in ensuring connectivity and communication, as well as assisting emerging technologies such as IoT and 5G.

Here an important point needs to be discussed. If we see at Table 1 and Table 2, the overall MAPE ranges from 62.7% to 79.9%. According to the Javed-Cudjoe scale to interpret the MAPE values (Javed & Cudjoe, 2020), the overall MAPE values greater than 30% signify inaccurate forecasts. If we look at the data carefully using the MAPE value at each point we can know the reason of this huge error in the simulation. For instance, if we take the case of secure internet servers in China, we can see that there were only 27,000 internet servers in 2015 and the figure rose to 2392000 servers by 2023. This is clearly an exponential trend. Just in one year, from 2016 to 2017, the servers boomed from 66 to 290. These kinds of significant jumps in data are not easy to handle. Thus, the MAPE was 503% in 2016 but was continuously reducing till it fall to 12.4% in 2023 (with small ups and downs). Now, even though the overall MAPE value is outrageously huge because of the significant difference between the actual data points it should be noted that the current study used original data without any filtration or normalization techniques. Also, the reduction in the MAPE value in the succeeding years only makes the succeeding simulations more accurate. Similar conclusions can be made for the secure internet servers in the US.

4. Conclusion

Secure internet servers and mobile cellular subscriptions are key derivers in the development of digital infrastructure, which is an important pillar of the socio-economic development of China and the US. The current study predicted the growth in secure internet servers and mobile cellular subscriptions till 2033 using the data from 2015 to 2023. To achieve these objectives the current study used the EGM (1,1, α, θ) model, an advanced grey forecasting model with two parameters (α and θ) that make it both adaptable and intelligent. The cellular subscriptions showed linearly increasing trend while internet servers showed exponentially increasing trend for both countries. In the absence of any disruptive technology, these trends are likely to continue in the future and digital infrastructure is likely to further improve in these countries. If we look at the results reported in the tables, one can argue that these trends underline the contributions of China in terms of expanding digital access and improving cybersecurity, as opposed to the US strategy, which promotes a more quality-driven approach centred on scalable, safe digital ecosystems, and technological innovation.

Digital infrastructure is a function of multiple components but the current study resort to just two components. In future, more components, and hence, more objects of forecasts, can be added in the study. Further, multi-variable grey forecasting models can also be used to improve the forecast accuracy, especially for the secure internet servers.

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