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Research Article

Modeling Signal Integrity in High-Frequency and Radio Frequency Circuits: A Comparison of Ohm's Law Variants

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Abstract

High-frequency circuit performance is significantly impacted by impedance variations, particularly within the low-resistance regime. Traditional Ohm's Law-based modeling approaches often fail to accurately predict circuit behavior in these conditions, leading to design inaccuracies and potential system failures. The Standard Ohm's Law-based model's prediction of infinite current as resistance approaches zero is unrealistic and hinders its application in practical scenarios. Despite recognizing these limitations, existing models have not comprehensively addressed the complex impedance behavior observed in high-frequency circuits. This paper introduces a modified version of the Ohm's Law incorporating an exponential correction term to overcome these challenges. The accuracy of the Modified Ohm's Law was evaluated through simulated experiments across a wide frequency range (1kHz to 1GHz) using various electronic components. The findings demonstrate the superior performance of the modified model in predicting currents under low-resistance and high-current conditions compared to the Standard Ohm's Law model. By providing finite and accurate current values, the proposed model effectively mitigates the unrealistic infinite current predictions of the standard approach. The enhanced predictive capabilities of the Modified Ohm's Law hold significant implications for high-frequency circuit design and analysis. Its application can improve performance and reliability in power electronics, telecommunications, and other high-frequency systems. By incorporating non-linear impedance behavior, the model offers a more accurate representation of real-world circuit conditions. Future research should focus on refining the exponential term's parameters to optimize the model's accuracy across a broader range of applications. Additionally, real-time implementation and hardware validation are essential to assess the model's practical utility in complex circuit environments.

1. Introduction

In modern technology, high-frequency circuits play a vital role in communication systems and RF applications [1-5]. However, these circuits are particularly susceptible to signal degradation caused by variations in impedance [6]. Signal integrity, which is preserving a signal's quality and reliability as it travels through a circuit, is paramount in these high-frequency applications [7]. Impedance variations can lead to many issues, including signal reflection, distortion, and loss [8, 9]. Traditionally, engineers have relied on Standard Ohm's Law to model the fundamental relationship between voltage (V), current (I), and resistance (R) in electrical circuits. This law states that the current flowing through a conductor is directly proportional to the voltage applied across its ends and inversely proportional to the resistance it offers. However, this relationship hinges on assuming a linear and static interaction between these parameters. This assumption breaks down in high-frequency circuits because impedance (Z), rather than resistance alone, dictates the opposition to current flow [10, 11]. Unlike resistance, which remains constant for a given material, impedance is a dynamic quantity that varies with frequency and other factors [12, 13]. Several factors contribute to this variation in impedance at high frequencies. Signals encounter additional resistive, inductive, and capacitive elements that are not explicitly included in the basic circuit model but arise from the circuit's physical layout, material properties, and signal frequency. These "parasitic elements" introduce non-linear behaviors into the circuit's response, rendering the Standard Ohm's Law incapable of accurately predicting the relationship between voltage and current [14]. While the Standard Ohm's Law is a cornerstone for basic circuit analysis, its limitations become apparent in high-frequency electronics [15-17].

The law's inherent assumption of linearity breaks down when dealing with rapidly changing signals and non-ideal components. In the past, this linear approximation sufficed for low-frequency applications with negligible impedance variations. Traditional design techniques could effectively manage these minor fluctuations. However, the modern high-speed and high-frequency electronics landscape presents a different scenario. Here, even minute impedance variations can significantly impact circuit behavior. This simplification inherent in Standard Ohm's Law leads to substantial inaccuracies in predicting how circuits will perform, making it challenging to ensure signal integrity [15, 18]. Such inaccuracies' consequences manifest in the inability to predict and mitigate signal degradation effectively. This, in turn, creates difficulties for engineers designing circuits that consistently deliver optimal performance under high-frequency conditions. Current solutions, such as complex impedance matching techniques and sophisticated simulation tools, offer some relief. These tools allow for detailed modeling and adjustments to circuit design [19-23]. However, they primarily function as workarounds, addressing the symptoms rather than the root cause of the problem. The fundamental limitation lies in the Standard Ohm's Law itself. It lacks the flexibility to capture the dynamic impedance variations observed in high-frequency circuits. As a result, it fails to provide a robust and accurate modeling framework that meets the demands of modern electronic design. The relentless pursuit of faster data rates and more robust communication systems fuels the continuous innovation in electronic devices. This is particularly true for applications like 5G networks, high-speed internet, and advanced computing systems, where the ever-growing data volumes demand efficient processing and transmission [24, 25]. To meet these challenges, devices are designed to operate at increasingly higher frequencies. However, this trend brings a new set of obstacles: impedance variations. Impedance variations in high-frequency circuits can inflict chaos on signal integrity, causing issues like reflection, distortion, and attenuation [26, 27]. These problems degrade the signal, leading to data transmission errors and reducing the communication system's efficiency and reliability. Traditional modeling techniques based on the Standard Ohm's Law are no longer sufficient to predict these variations accurately. The Standard Ohm's Law assumes a linear relationship between voltage, current, and resistance, which does not hold in high-frequency circuits [7, 15, 17, 18].

In reality, these circuits exhibit complex, non-linear impedance behaviors due to factors like parasitic capacitances and inductances within the components and the skin effect, where high-frequency AC currents tend to concentrate on the surface of conductors [28, 29]. As the operating frequency increases, impedance variations within circuits become increasingly significant. To guarantee reliable and efficient data transmission in these high-frequency domains, traditional modeling techniques fall short, necessitating a shift towards approaches that account for these complex phenomena. While a foundational principle, the Standard Ohm's Law exhibits limitations in high-frequency circuits. Its linear relationship between voltage and current fails to capture the rapid impedance changes at these frequencies [17]. This shortcoming can lead to unrealistic predictions, particularly in scenarios with very low resistance values. The Standard Ohm's Law (also termed in this paper as the traditional Ohm's Law) would predict theoretically infinite currents in such situations, which is physically impossible [15].

The Modified Ohm's Law addresses these limitations by introducing an exponential term into the equation [15]. This adjustment allows for a more precise representation of impedance behavior, especially at low resistance values. The exponential term aims to ensure that the predicted current remains finite even in extreme high-frequency scenarios, providing a more accurate and stable prediction of circuit behavior. By incorporating this exponential term, the Modified Ohm's Law effectively captures the rapid impedance fluctuations that the Standard Ohm's Law overlooks. This improvement is crucial for designing circuits that maintain signal integrity. With a more accurate picture of impedance behavior, engineers can better predict and mitigate the negative effects of these variations. The realistic depiction of circuit behavior facilitated by the modified law empowers the development of robust, high-performance communication systems that can handle the ever-growing demands of modern technology. Therefore, this paper has a twofold objective: firstly, to address the inherent limitations of Standard Ohm's Law in accurately modeling impedance variations in high-frequency circuits, and secondly, to investigate the Modified Ohm's Law as a superior application alternative. Including an exponential term in the modified equation allows a more accurate representation of the non-linear impedance behavior observed in high-frequency applications. This enhancement aims to significantly improve the accuracy of signal integrity analysis, leading to more precise design and optimization of modern high-frequency circuits. Ultimately, this approach minimizes signal distortion and ensures reliable data transmission.

Providing engineers with a more robust predictive tool compared to conventional methods, the Modified Ohm's Law has the potential to mark a paradigm shift in high-frequency circuit design. The Modified Ohm's Law validation hinges on a comparative analysis with the standard law's predictions in various high-frequency contexts. We can use computational simulations and empirical studies to demonstrate that the modified law offers a more accurate representation of impedance behaviour in real-world scenarios, particularly at low-resistance values where the standard law predicts unrealistic infinite currents. This validation highlights the need to adopt this innovative model in modern applications. By ensuring greater precision and reliability in high-frequency circuit design, the Modified Ohm's Law bridges the theoretical-practical gap, paving the way for advancements in this field.

Consequently, it can support the development of faster, more dependable electronic systems and communication technologies. The validation framework outlined in this paper employs a computational approach to rigorously assess the performance of the Modified Ohm's Law across a spectrum of high-frequency circuit conditions. By systematically varying resistance values and circuit configurations, the framework comprehensively compares the Modified Ohm's Law and the Standard Ohm's Law in predicting current behavior. Through detailed simulations, the paper demonstrates the superior accuracy of the modified model in capturing complex impedance variations inherent in high-frequency circuits. This computational methodology provides a robust foundation for validating the practical applicability of the Modified Ohm's Law in real-world scenarios.

2. Literature Review

2.1. Historical Perspectives

The Standard Ohm's Law, a cornerstone of electrical engineering since its formulation by Georg Simon Ohm in the early 19th century, relates voltage (V), current (I), and resistance (R) through the linear equation V=IR [30]. This simple relationship has been immensely valuable for analyzing and designing circuits, allowing engineers to predict their behavior under various conditions. However, practical limitations of the law emerged early on, particularly in scenarios involving shallow resistance values [15, 30]. The Standard Ohm's Law suggests that a meagre resistance should result in a proportionally high current for a given voltage. In extreme cases, this implies the possibility of infinite current, a theoretical construct that deviates significantly from real-world observations where factors like material limitations and heat dissipation come into play [15, 30]. This discrepancy between theoretical predictions and practical experience underscored the need for more rigorous models to account for electrical circuits' complexities under extreme conditions.

Consequently, researchers began venturing beyond the linear paradigm of the Standard Ohm's Law, investigating how material properties, frequency, and other dynamic factors influence circuit behavior [15-

18, 30]. The evolution of material science has played a significant role in attempts to overcome the limitations of the Standard Ohm's Law [31]. Advances in materials such as superconductors, semiconductors, and conductive polymers have all been aimed at improving the performance and reliability of electrical circuits [32]. For instance, superconductors, which exhibit zero resistance at very low temperatures, initially seemed to offer a solution to the limitations posed by traditional conductors. However, the practical application of superconductors is constrained by the need for extremely low temperatures, which is not feasible for most high-frequency applications [32-36].

Similarly, semiconductor materials have revolutionized electronics, enabling the miniaturization and enhancement of circuit components [37, 38]. Techniques such as doping and the development of heterostructures have improved the performance of semiconductor devices [39]. Nevertheless, these materials still face challenges related to impedance variations at high frequencies. For example, while semiconductors like silicon and gallium arsenide are effective at certain frequencies, they may exhibit significant impedance variations at very high frequencies, leading to signal integrity issues [40].

Conductive polymers, another innovative material class, offer advantages like flexibility and ease of processing, making them attractive for various electronics applications. However, their conductivity is generally lower than traditional metals, and they also exhibit impedance variations that complicate their use in high-frequency circuits [41]. These advancements in material science have provided valuable tools for improving circuit performance but have not fully addressed impedance variations at high frequencies. Even when applied to these advanced materials, the linear model of Ohm's Law fails to adequately capture the non-linear behavior observed in real-world high-frequency scenarios [30, 31]. This ongoing challenge highlights the need for a more precise approach to modeling impedance and ensuring signal integrity in modern circuits. The Modified Ohm's Law, incorporating an exponential term to account for these variations, represents a promising step towards addressing these limitations and improving the accuracy of high-frequency circuit analysis [15].

2.2. Current Perspectives

In modern high-frequency circuits, maintaining signal integrity is paramount for communication systems and RF applications. Impedance variations within these circuits can significantly degrade signals, leading to reflection loss and ultimately hampering overall performance and reliability [42, 43]. Current methods to address these challenges involve advanced modeling techniques and circuit design optimizations. However, these approaches often struggle to accurately predict and mitigate the impact of impedance changes, especially at high frequencies [43, 44]. This inability to precisely model these variations translates to suboptimal circuit performance and recurring reliability issues [43]. Material science has offered some solutions to mitigate the limitations of the Standard Ohm's Law in high-frequency applications. Developing high-performance substrates and conductive materials with lower dielectric losses has demonstrably improved the propagation characteristics of RF signals [45-47].

Advanced materials like low-loss ceramics and high-purity copper have been utilized to reduce signal degradation and impedance mismatches [48, 49]. However, even with these advancements, challenges remain. Material imperfections, inconsistencies during manufacturing, and environmental factors like temperature fluctuations can still introduce unpredictable impedance variations that the Standard Ohm's Law cannot accurately account for. Software development has also emerged as a critical tool for tackling impedance issues in high-frequency circuits. Electromagnetic simulation tools, like HFSS (High-Frequency Structure Simulator) and ADS (Advanced Design System), empower designers to model complex RF circuits and achieve more accurate predictions of impedance behavior [50, 51]. These tools leverage sophisticated algorithms to simulate the electromagnetic fields and their interactions within the circuit, offering valuable insights into potential impedance mismatches and signal integrity problems. However, despite their advanced capabilities, limitations exist with these simulation tools. They often rely on approximations and assumptions that might not fully capture impedance variations' non-linear and dynamic characteristics at extremely high frequencies.

Additionally, the accuracy of the simulations hinges heavily on the quality of the input data and the precision of the material properties incorporated into the models [52]. Existing technologies like adaptive filtering and matching networks have been used to address impedance variations. Adaptive filtering techniques dynamically adjust signal processing parameters to account for impedance changes, while impedance matching networks minimize reflections by aligning the load impedance with the source impedance [53-55].

However, these approaches also have limitations. Adaptive filtering can introduce latency and complexity into the system, and impedance-matching networks might not be suitable for accommodating wide variations in impedance across different operating conditions [53-55]. Hence, while advancements in material science and software development have significantly improved signal integrity in high-frequency circuits, their techniques still fall short of eliminating the challenge of impedance variations. The limitations of the Standard Ohm's Law in accurately modeling these variations highlight the need for innovative solutions, such as the Modified Ohm's Law model, which is shown to provide a more precise representation of impedance behavior in high-frequency applications in this paper.

2.3. The Need for Alternative Possible Solutions

The limitations of traditional circuit analysis methods become increasingly apparent when dealing with high-frequency circuits. While previous sections alluded to this challenge, it is crucial to emphasize the need for innovative modeling techniques to accurately predict impedance variations' impact on signal integrity. Standard circuit analysis, often grounded in Standard Ohm's Law, assumes a linear relationship between voltage, current, and resistance. This approach proves inadequate at high frequencies because it fails to capture the non-linear behavior of impedance. Impedance in high-frequency circuits becomes a complex function influenced by parasitic capacitance, inductance, and skin effect [14, 22, 29]. These factors cause impedance to deviate significantly from the simple resistance model of Ohm's Law, leading to inaccurate predictions of signal behavior and potential integrity issues. The Modified Ohm's Law, introduced to address these limitations, presents a promising solution by incorporating an exponential term. This modification accurately represents impedance behavior, particularly in low-resistance scenarios [15]. It ensures that resistance never truly reaches zero, avoiding the paradox of infinite current predicted by the Standard Ohm's Law. Instead, the current increases exponentially as resistance decreases, a more realistic depiction that aligns with practical observations [15, 18].

2.4. Overview of the Modified Ohm's Law

To address the shortcomings of the Standard Ohm's Law, the modified equation redefines the relationship between resistance, current, and a parameter referred to as "short resistance," denoted as R_{short} to account for non-linear behaviors at low resistances [15]. The traditional Ohm's Law, $V = I \times R$, where V is voltage, I is current, and R is resistance, is modified to account for non-linear behaviors by incorporating an exponential term. This approach is grounded in the premise that resistance R is a function of some variable x, leading to the expression $R = R(x)$. Assuming $R(x)$ can be expressed as an exponential function of x, we have $R(x) = a \times e^{bx}$, where a and b are constants. Substituting this into the Modified Ohm's Law equation, we get $\left(I = \frac{V}{a \times e^{bx}}\right)$. Introducing a reference current I_0 when $x = 0$, such that $I_0 = \frac{V}{a}$, the equation simplifies to; $(I = I_0 \times e^{-bx})$.

To adapt this for practical scenarios, we define R_{short} as the change in resistance from its reference value R_0, so that $R(x) = R_0 + R_{short}$. This leads to the final form of the Modified Ohm's Law;

$$\left(I_{modified} = a \times e^{\frac{R_{short}}{R_0}}\right) \tag{1}$$

Where, a is a scaling factor determined by the reference resistance and voltage, and R_0 is the reference resistance.

Suitability of the Modified Ohm's Law: Modified Ohm's Law is particularly suited for high-frequency circuit analysis, where traditional models fall short. This model aligns with the real-world behavior of materials and circuits under high-frequency conditions by ensuring that current remains finite even as resistance approaches zero. It accounts for the exponential increase in current with decreasing resistance, a phenomenon observed in practical scenarios such as semiconductor devices and high-current applications.

Moreover, the inclusion of the parameter (x) allows the Modified Ohm's Law to model various factors influencing resistance. These factors include the length and cross-sectional area of the conductor, temperature, material properties, electromagnetic interactions, and external environmental conditions [15]. This flexibility makes the Modified Ohm's Law a robust tool for accurately predicting impedance changes and their effects on signal integrity.

3. Methodology

A comprehensive simulation framework was precisely constructed to rigorously evaluate the efficacy of the Modified Ohm's Law in the complex domain of high-frequency circuits. Central to this framework was the accurate representation of impedance variations and their consequential impact on signal integrity. A particular emphasis was placed on simulating real-world conditions, especially those characterized by low resistance and high current, which often pose significant challenges for circuit design and performance.

To optimize computational efficiency and facilitate in-depth analysis, the simulation framework leveraged the capabilities of Python libraries. NumPy's array operations accelerated numerical computations, while SciPy's advanced functions enabled precise modeling of the non-linear resistive behavior inherent in high-frequency circuits. Matplotlib's visualization tools produced clear and informative graphical representations of current behavior across varying resistance and voltage conditions, aiding in data interpretation and comparative analysis. The selection of simulation parameters was guided by the need to accurately reflect real-world high-frequency circuit operation. Resistance values were systematically varied from near-zero to slightly below the baseline resistance (R_0) to encompass the critical low-resistance regime often encountered in practical applications. Voltage levels were similarly adjusted to simulate a range of operational conditions, starting with a standard 1V for low-voltage scenarios and progressing to higher values representative of power electronics and telecommunications systems. By precisely considering real-world conditions and employing advanced computational tools, this paper aims to address the limitations of existing models in capturing the complex impedance behavior prevalent in high-frequency circuits.

3.1. Low-Resistance Prediction

Standard Ohm's Law: The Standard Ohm's Law is given by: $\left(I = \frac{V}{R}\right)$ where I is the current, V is the voltage, and R is the resistance. For this scenario, the Standard Ohm's Law is applied as $\left(I = \frac{V}{R_0 + R_{short}}\right)$, where R_0 is the inherent resistance and R_{short} is and any additional resistance.

Modified Ohm's Law. As earlier established, the Modified Ohm's Law introduces an exponential factor to address the limitations of the standard model in low-resistance conditions. It is expressed as: $I = \frac{V}{R_0} \times \left(e^{\frac{R_{short}}{R_0}}\right)$. Here, R_0 is a baseline resistance, R_{short} is the short resistance, and V is the voltage.

This modification ensures that the current prediction remains finite even as R_{short} approaches zero.

3.1.1. Simulation Algorithm

Table 1. Simulation Algorithm Framework

Parameter Initialization	● **Voltage (V).** Set at $1V$ for low-voltage scenarios and varied for different experiments. ● **Baseline Resistance (R_0).** Different values (0.01Ω, 0.05Ω, 0.1Ω, 0.2Ω) to represent various baseline conditions. ● **Short Resistance (R_{short}).** Ranged from close to zero up to a value just below R_0.
Current Calculation	● For the Standard Ohm's Law, the current was calculated using R_0 alone. ● Current was calculated using the exponential model for the Modified Ohm's Law.
Comparative Analysis	● The results from both models were plotted for each set of conditions to compare their predictions visually.

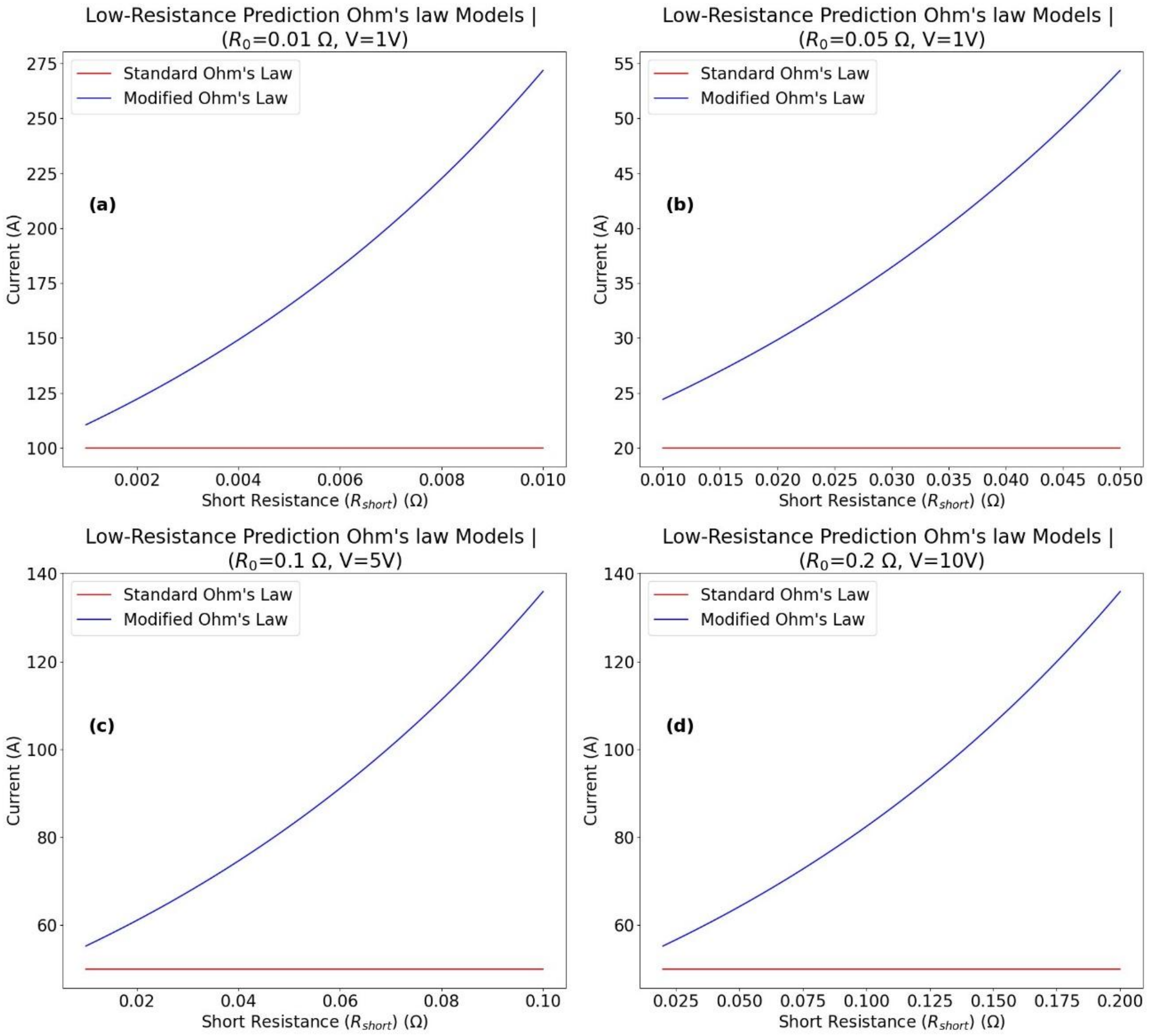

Figure 1. Low-Resistance Prediction Ohm's Law Models. ((a) $R_0 = 0.01\Omega$, $V = 1V$; (b) $R_0 = 0.05\Omega$, $V = 1V$; (c) $R_0 = 0.1\Omega$, $V = 5V$; (d) $R_0 = 0.2\Omega$, $V = 10V$. The plots compare the Standard Ohm's Law (red) and Modified Ohm's Law (blue) predictions, highlighting the modified model's ability to provide realistic current values under low-resistance conditions).

Table 1 outlines the simulation algorithm used to evaluate the efficacy of the Modified Ohm's Law model compared to the Standard Ohm's Law model. The framework details parameter initialization, current calculation methods, and comparative analysis procedures.

Remark *(On simulation logic)* :The logic followed in this simulation framework will be employed in the subsequent analysis sections, with specific experimental parameters varied suitably. This approach ensures a consistent and thorough evaluation of the Modified Ohm's Law across different high-frequency circuit scenarios, providing valuable insights into its application and effectiveness.

Figure 1. depicts the low-resistance prediction results for the standard and Modified Ohm's Law models across four experimental scenarios.

The results in Figure 1 illustrate how Standard Ohm's Law predicts a constant current based on the baseline resistance R_0, regardless of the additional short resistance R_{short}. In contrast, the Modified Ohm's Law incorporates an exponential term that accounts for the short resistance, ensuring that the current predictions remain finite and realistic as R_{short} approaches zero. This distinction is evident across all four experiments, showcasing the Modified Ohm's Law model's robustness and accuracy in scenarios where the Standard Ohm's Law fails to provide practical predictions. In Figure 1 (a) (Low-Resistance Prediction with; $R_0 = 0.01\Omega,\ V = 1V$) scenario, the Modified Ohm's Law showed a controlled exponential increase in current as R_{short} decreased. The standard model predicted a constant current determined by R_0 alone. The exponential term in the modified model effectively prevented the unrealistic prediction of infinite current, validating its application in low-resistance conditions. In Figure 1 (b) (Low-Resistance Prediction with; $R_0 = 0.05\Omega,\ V = 1V$)-With a slightly higher baseline resistance, the Modified Ohm's Law continued to predict a finite but exponentially increasing current.

The standard model, again, showed a constant current. This further demonstrated the modified model's robustness in preventing unrealistic predictions in the low-resistance domain. In Figure 1 (c) (Low-Resistance Prediction with; $R_0 = 0.1\Omega,\ V = 5V$)-Increasing both the baseline resistance and the voltage, the Modified Ohm's Law maintained its predictive capability. The exponential increase in current remained finite and realistic. The Standard Ohm's Law model's prediction stayed constant, highlighting the Modified Ohm's Law model's advantage in varying baseline conditions and higher voltage scenarios. Finally in Figure 1 (d) (Low-Resistance Prediction with; $R_0 = 0.2\Omega,\ V = 10V$)-WhiThe Modified Ohm's Law continued to provide finite current predictions, which offer the highest resistance and voltage scenario, avoiding the divergence seen with the standard model under similar conditions. This emphasized the modified model's capability to handle high-current applications without yielding impractical results.

Through this analysis, the Modified Ohm's Law proved superior with its exponential term advantage in scenarios where resistance values approach zero. It provided realistic, finite current predictions, effectively addressing the limitations of the Standard Ohm's Law. This makes the Modified Ohm's Law model an excellent tool for high-frequency circuit analysis, particularly in low-resistance measurements and high-current applications. The parameters used in the simulation (voltage and baseline resistance) demonstrated the modified model's robustness across various conditions, validating its efficacy as the best predictive model for these scenarios.

3.2. High Current Prediction

In the high-current prediction scenario, the simulation framework aimed to evaluate the performance of the Modified Ohm's Law under conditions of substantial current, which often leads to significant impedance variations. The experiments focused on maintaining signal integrity in high-frequency domains, where circuits are subjected to large currents and minimal resistance. This scenario is particularly relevant for power electronics and telecommunications applications, where accurate impedance modeling is crucial for system reliability and performance. Two experiments were performed for this simulation: Case 1 (Parameters; R_{short}, V, R_0, and resistance (Ω)) and Case 2 (Parameters; V, R_0, a, and Resistance (Ω)).

Case 1 (High-Current Prediction): The first case of the high-current prediction involved varying resistance values and assessing the current predictions using both the Standard Ohm's Law and Modified Ohm's Law. The parameters included a high voltage (V), a reference resistance (R_0), and an additional short resistance (R_{short}) to simulate real-world conditions where resistance fluctuates. The Modified Ohm's Law introduced an exponential term to account for the non-linear resistance behaviour at high frequencies, which the Standard Ohm's Law fails to capture accurately. The simulation steps involved calculating the current using both laws across various resistance values. For each parameter combination, the constant "a" was determined as the ratio of voltage to reference resistance. The Standard Ohm's Law predicted current based on the sum of the reference and varying resistance, while the Modified Ohm's Law incorporated the exponential term to predict current as a function of the short resistance and reference resistance. Figure 2 illustrates the results of the high-current prediction experiments. In each panel, the red curve represents the current predictions using the Standard Ohm's Law, while the blue curve shows the predictions using the Modified Ohm's Law. The plots demonstrate the limitations of Standard Ohm's Law, which fails to account for the exponential rise in current as resistance decreases. However, the Modified Ohm's Law provides a more accurate and realistic prediction, showcasing its efficacy in high-current applications.

These plots compare the Standard Ohm's Law (red) and Modified Ohm's Law (blue) predictions, highlighting the modified model's ability to maintain accurate current predictions under high-current conditions. In all panels (a)-(d)), the resistance ranged uniformly between 0.000Ω and 0.010Ω).

Case 2 (High-Current Prediction): In the second case of the high-current prediction scenario, the simulation framework explored the Ohm's Law variants' performance under various voltage, reference resistance, and short resistance conditions. This case involved multiple experiments designed to highlight different aspects of high-current behavior in electrical circuits. The first experiment varied the short resistance while keeping the voltage and reference resistance constant. The simulation demonstrated how the Modified Ohm's Law, with its exponential term, provided a more accurate current prediction than the Standard Ohm's Law, especially at lower resistance values. This is evident in the results, where the Standard Ohm's Law underestimated the current, while the Modified Ohm's Law showed a more pronounced increase, reflecting the non-linear resistance behavior at high frequencies (Figure 3a).

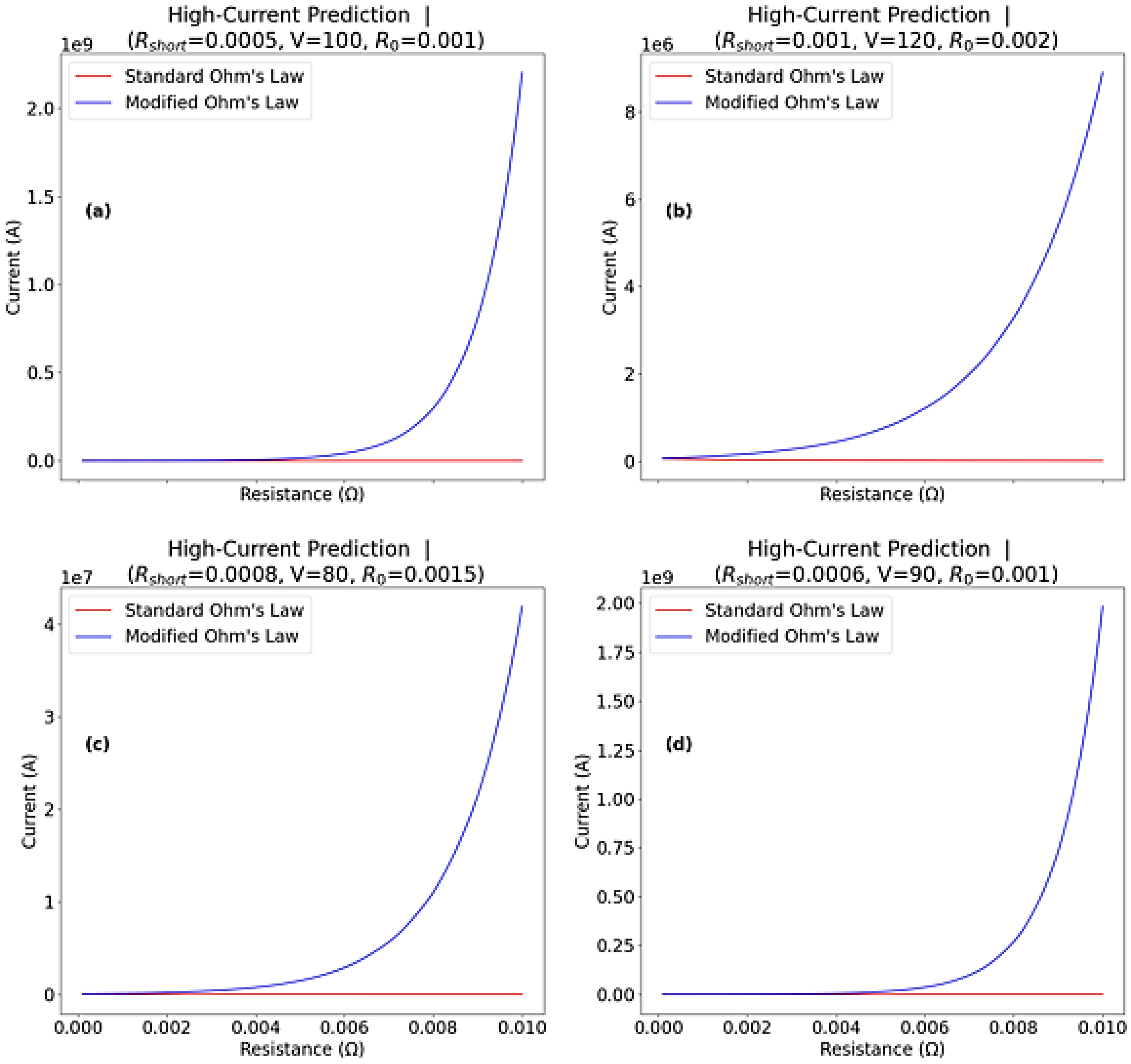

Figure 2. High-Current Prediction on Ohm's Law Models for R_{short}, V and R_0. ((a) $R_{short} = 0.0005$, $V = 100V$, $R_0 = 0.001$; (b) $R_{short} = 0.001\Omega$, $V = 120V$, $R_0 = 0.002\Omega$; (c) $R_{short} = 0.0008\Omega$, $V = 80V$, $R_0 = 0.0015\Omega$; (d) $R_{short} = 0.0006\Omega$, $V = 90V$, $R_0 = 0.001\Omega$.

In the second experiment, the voltage was increased while maintaining the same reference resistance as the first experiment. This change in voltage resulted in a higher scaling factor, which in turn amplified the differences between the two laws. The Standard Ohm's Law continued to show a linear relationship, while the Modified Ohm's Law accurately depicted the exponential rise in current with decreasing resistance, highlighting its robustness in high-voltage scenarios (Figure 3b).

The third experiment further examined the effect of varying the reference resistance. The reference resistance was reduced, resulting in an even larger scaling factor. The Modified Ohm's Law's predictions became more distinct, showcasing its ability to adapt to different baseline resistances. This adaptability is critical for applications where reference resistances vary significantly, such as power electronics and telecommunications (Figure 3c).

The final experiment directly investigated the impact of varying the scaling factor, using a range of values while keeping the voltage and reference resistance constant. This experiment demonstrated how the Modified Ohm's Law could flexibly model current predictions across different scaling scenarios. The results reinforced the importance of accurately determining the scaling factor to maintain signal integrity and reliability in high-current applications (Figure 3d). Overall, the simulation results across all experiments highlighted the superior performance of the Modified Ohm's Law in predicting current under high-current conditions. With its linear approach, Standard Ohm's Law consistently underestimated current, failing to account for the exponential characteristics of resistance at high frequencies. The Modified Ohm's Law, including the exponential term, provided a much-needed correction, making it a vital tool for high-frequency domains.

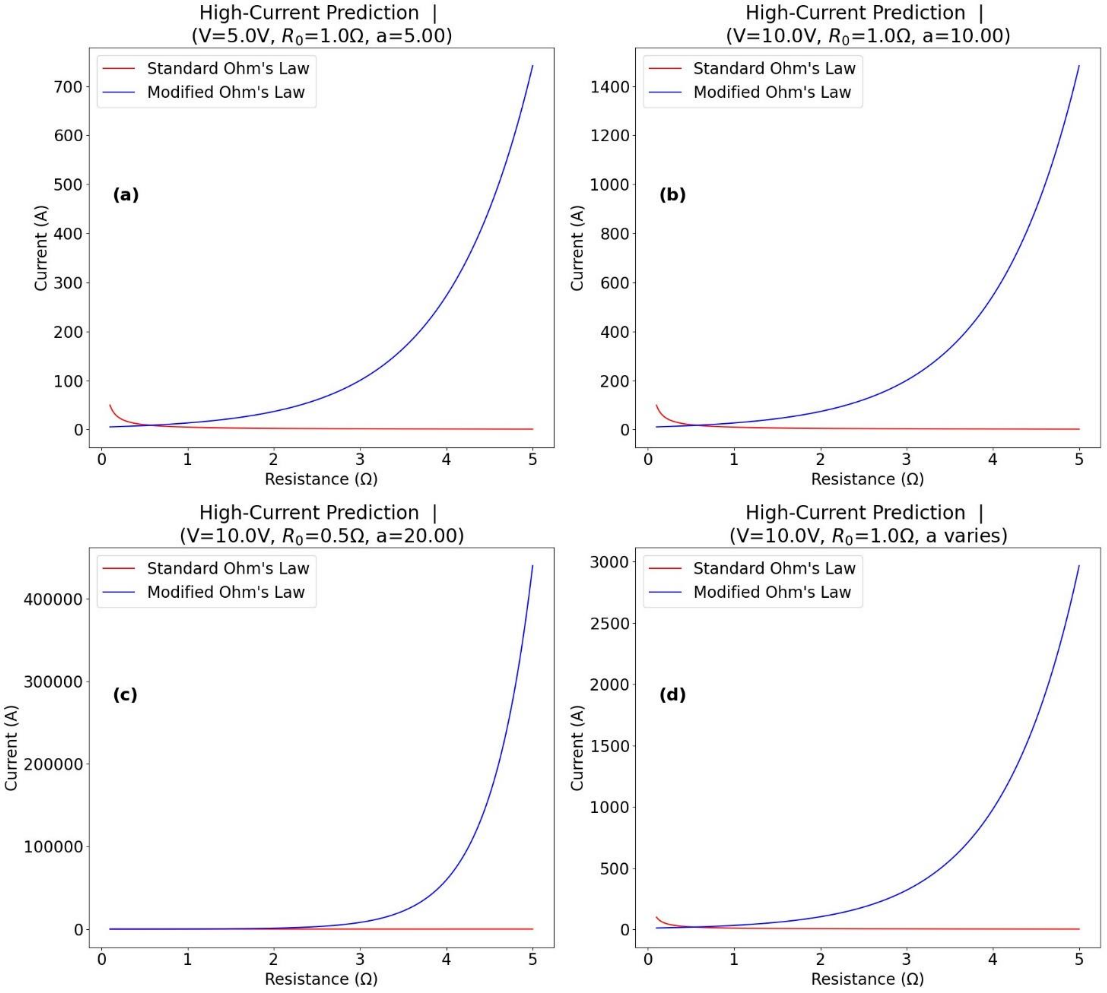

Figure 3. High-Current Prediction analysis for V, R_0 and a. ((a) $V = 5V$, $R_0 = 1\Omega$, $a = 5$; (b) $V = 10V$, $R_0 = 1\Omega$, $a = 10$; (c) $V = 10V$, $R_0 = 0.5\Omega$, $a = 20$; (d) $V = 10V$, $R_0 = 1\Omega$, varying a.

These plots compare the Standard Ohm's Law (red) and Modified Ohm's Law (blue) predictions, highlighting the modified model's ability to maintain accurate, current predictions under various high-current conditions in all panels (a)-(d)), the resistance ranged uniformly between 0.0Ω and 0.5Ω).

3.3. Practical Scenarios of the Ohm's Law Variants

3.3.1. Advanced Design and Analysis of High-Frequency Circuits

The simulation for advanced design and analysis explored the application of Modified Ohm's Law in high-frequency circuits. This investigation focused on how the modified models of Ohm's Law can provide more accurate predictions and insights into the behavior of circuits operating at frequencies of $1kHz$, $1MHz$, and $1GHz$. The scenarios examined varied parameters such as short resistance (R_{short}), voltage (V), and reference resistance (R_0), reflecting typical conditions encountered in semiconductor devices, thermistors, varistors, and materials with non-uniform resistivities. In each experiment, the simulation calculated and compared the currents predicted by the standard and Modified Ohm's Laws across a range of resistance values. This analysis aimed to demonstrate the non-linear resistance behaviour at high frequencies and validate the Modified Ohm's Law's effectiveness in capturing these dynamics. By varying R_{short}, V, and R_0, the simulation highlighted how different configurations could practically impact current predictions. The simulation results are depicted in Figure 4.

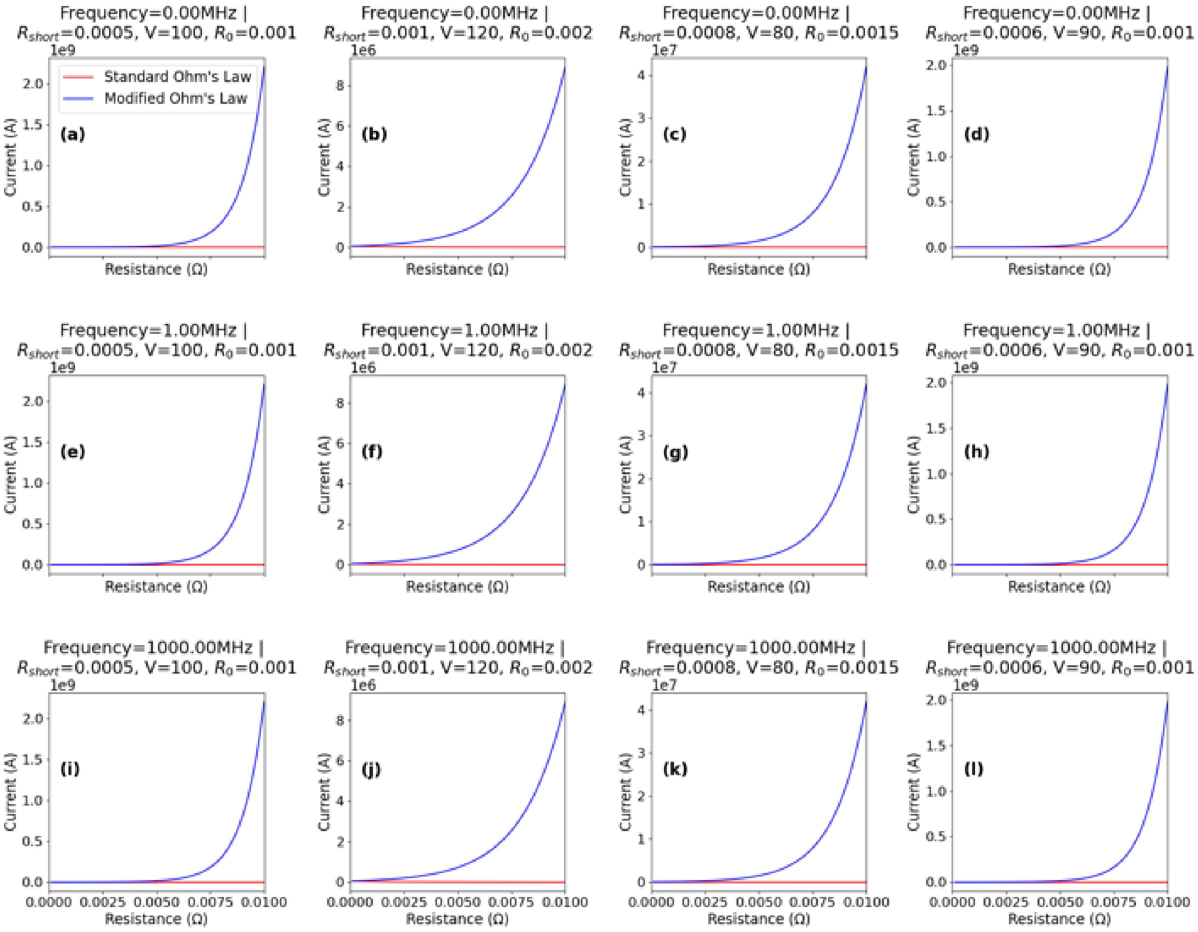

Figure 4. Advanced design and Analysis of High-Frequency Circuit Analysis. ((a-d) at $1kHz$, (e-h) at $1MHz$, (i-l) at $1GHz$.

These plots compare the Standard Ohm's Law (red) and Modified Ohm's Law (blue) predictions, demonstrating the Modified Ohm's Law model's ability to predict current across various high-frequency conditions accurately.

Each panel details a different combination of R_{short}, V, and R_0, illustrating the versatility and accuracy of the Modified Ohm's Law in advanced circuit design and analysis. In all panels (a)-(l)), the resistance ranged uniformly between 0.000Ω and 0.010Ω).

For the frequency of $1kHz$, the Standard Ohm's Law showed a linear decrease in current as resistance increased. However, the Modified Ohm's Law displayed a more complex profile, particularly at lower resistance values, predicting significantly higher currents. This discrepancy underscored the modified law's ability to account for the exponential behavior of resistance that the standard law overlooked (Figure 4a to 4d). At $1MHz$, the differences between the standard and modified predictions became more pronounced. As the frequency increased, the non-linear effects of resistance were more evident. The Modified Ohm's Law continued to predict higher currents at low resistances, aligning better with the expected behavior in high-frequency applications such as power electronics and telecommunications (Figure 4e to 4h). For the highest frequency of $1GHz$, the Modified Ohm's Law's advantages were most apparent. The standard law's predictions diverged significantly from the modified law's, especially at the lower end of the resistance spectrum. The exponential increase in current predicted by the modified law accurately reflected the high-frequency effects, making it a critical tool for designing and analyzing circuits operating in the gigahertz range (Figure 4(i) to 4(l)).

These results across all frequencies and parameter variations highlighted the Modified Ohm's Law's superiority in modeling high-frequency circuit behavior. With its linear approach, the Standard Ohm's Law consistently underestimated the current, failing to capture the complex dynamics at high frequencies. In contrast, the Modified Ohm's Law, incorporating an exponential term, provided a more realistic representation of current behavior, crucial for applications involving semiconductor devices, thermistors, varistors, and materials with non-uniform resistivities.

3.3.2. Comparative Analysis of the Ohm's Law Variants in Various Electronic Devices

In this analysis, we examined the behavior of various devices—Semiconductors, Thermistors, Varistors, and materials with Non-uniform Resistivities—using both standard and Modified Ohm's Law. This section aims to understand how these devices respond to different voltage levels and resistance variations, demonstrating the efficacy of the Modified Ohm's Law in capturing non-linear resistive properties. The simulation involved four distinct scenarios, each tailored to a specific device type. For each scenario, the parameters voltage (V), reference resistance (R_0), and the short resistance (R_{short}) were varied. This approach allowed us to observe and compare the currents predicted by standard and Modified Ohm's Law across a wide resistance range. In the first scenario, representing a semiconductor device, we applied a voltage of $5.0V$ with a reference resistance (R_0) of 1.0Ω, and varied R_{short} from 0.1Ω to 5.0Ω. The results showed that while the Standard Ohm's Law predicted a linear decrease in current with increasing resistance, the Modified Ohm's Law provided a more accurate and higher current prediction, particularly at lower resistance values. This highlighted the semiconductor's non-linear behavior, which the modified law successfully captured (Figure 5a). The second scenario focused on a thermistor, applying $10.0V$ with $R_0 = 0.5\Omega$. Similar to the first scenario, R_{short} was varied from 0.1Ω to 5.0Ω. The results reinforced the Modified Ohm's Law's superior predictive capability, showing significantly higher currents at lower resistances. This is crucial for thermistors exhibiting resistance changes with temperature variations, underscoring the Modified Ohm's Law's applicability in accurately modeling such non-linearities (Figure 5b).

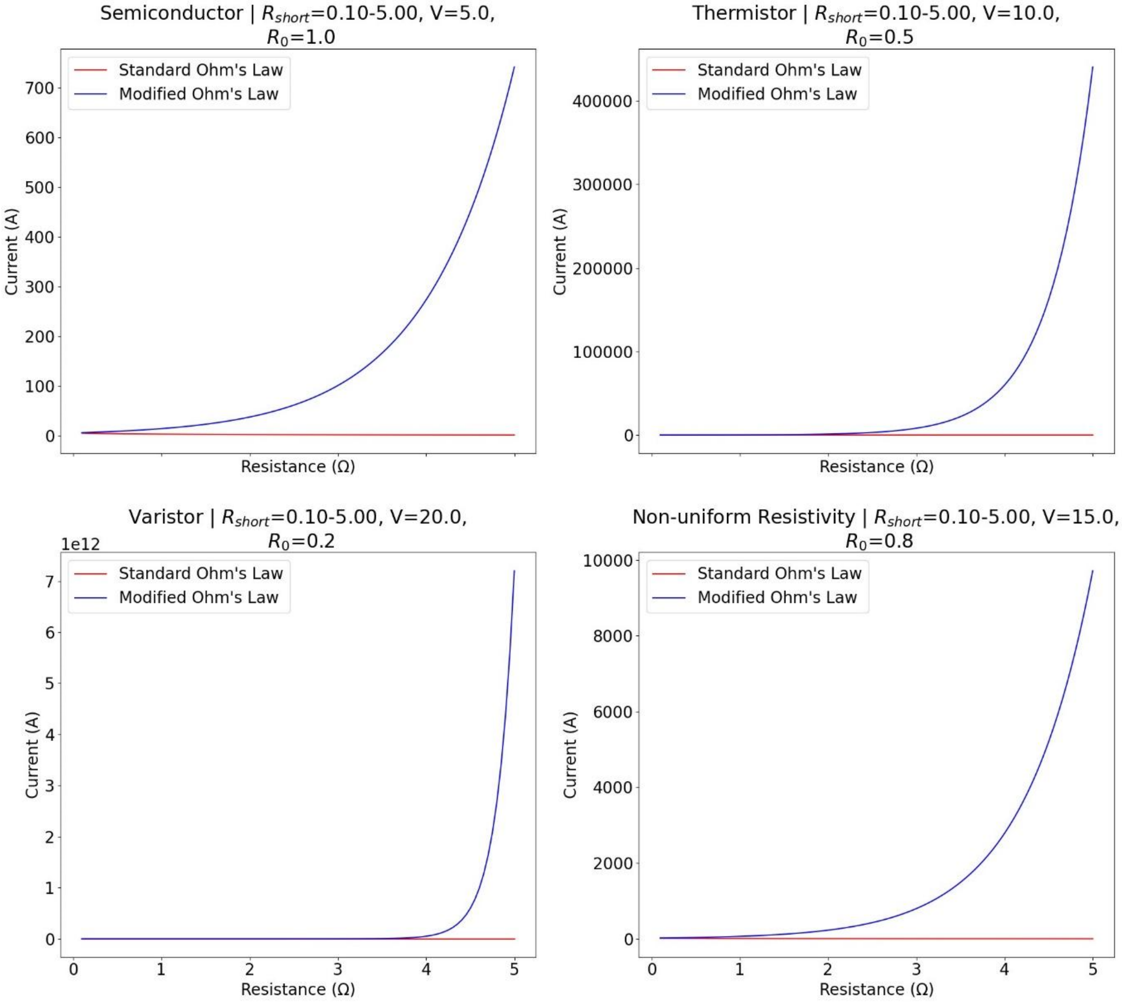

Figure 5. Comparative Current Predictions Using Standard and Modified Ohm's Law. ((a) Semiconductor, (b) Thermistor, (c) Varistor, (d) Non-uniform Resistivity Material. Each plot compares the Standard Ohm's Law (red) with the Modified Ohm's Law (blue), highlighting the latter's ability to capture the non-linear behavior of these devices across different resistance ranges and voltages).

In the third scenario, for a varistor, we used a higher voltage of $20.0V$ with a reference resistance of 0.2Ω. The R_{short} range remained from 0.1Ω to 5.0Ω. The Modified Ohm's Law again outperformed the

Standard Ohm's Law, especially at low resistance values, reflecting the varistor's ability to handle high voltage spikes by showing a sharp increase in current. This scenario demonstrated the modified law's effectiveness in high-voltage applications where standard predictions fall short (Figure 5c). The fourth scenario analyzed materials with non-uniform resistivities, applying a voltage of $15.0V$ with $R_0 = 0.8\Omega$. The R_{short} range was the same as previous scenarios. Here, the Modified Ohm's Law continued to provide a better fit for the current behavior, capturing the complex resistive properties of these materials, which are often encountered in advanced electronic components and materials science (Figure 5(d)).

Overall, this comparative analysis revealed the Modified Ohm's Law's capability to more accurately predict the current behavior in various devices under different conditions. The exponential term in the modified law allowed for better modeling of non-linear resistance effects, which are not accounted for in the standard linear approach. These results, presented in Figure 5, highlight the importance of considering non-linear resistive properties in advanced electronic design and analysis. This insight is particularly valuable for applications in semiconductors, thermistors, varistors, and materials with non-uniform resistivities, enhancing the precision and reliability of high-performance electronic systems.

3.3.2 Signal Integrity Analysis in High-Frequency Circuits: A Comparative Case

This section investigates the current behavior in high-frequency circuits using both Standard Ohm's Law and Modified Ohm's Law. The analysis focuses on four high-frequency systems: WiFi Routers, Cellular Base Stations, Satellite Communications, and Radar Systems. The aim was to understand how these systems respond to different voltage levels and resistance variations, highlighting the Modified Ohm's Law's ability to capture the non-linear resistive properties often encountered in high-frequency circuit applications. The paper considered four scenarios, each representing a different high-frequency system. For each scenario, the voltage (V), reference resistance (R_0), and the short resistance (R_{short}) values were varied. This setup allowed for a comprehensive examination of current predictions by both standard and Modified Ohm's Law across various resistances. For the WiFi Router scenario, a voltage of $12.0V$ and a reference resistance (R_0) of 1.0Ω were used, with R_{short} ranging from 0.1Ω to 5.0Ω. The Standard Ohm's Law predicted a linear decrease in current with increasing resistance.

In contrast, the Modified Ohm's Law, incorporating an exponential term, showed a higher current prediction, particularly at lower resistances. This indicates the WiFi Router's complex resistive properties and highlights the modified law's capability to model such behavior accurately (Figure 6a). The Cellular Base Station scenario applied a higher voltage of $24.0V$ with a reference resistance 0.5Ω. Similar to the WiFi Router, R_{short} was varied from 0.1Ω to 5.0Ω. The Modified Ohm's Law again outperformed the standard law, especially at lower resistance values. This enhanced accuracy is crucial for cellular base stations, which require precise current predictions to maintain signal integrity and efficient power management under varying load conditions (Figure 6b). For the Satellite Communication scenario, a voltage of $36.0V$ with a reference resistance of 0.2Ω was used. The Modified Ohm's Law provided significantly higher current predictions at lower resistances compared to the standard law. This scenario demonstrated the importance of accurate modeling for satellite communication systems, where non-linear resistive effects can impact signal quality and transmission reliability. The Modified Ohm's Law's ability to account for these effects ensures a more robust system design and performance (Figure 6c).

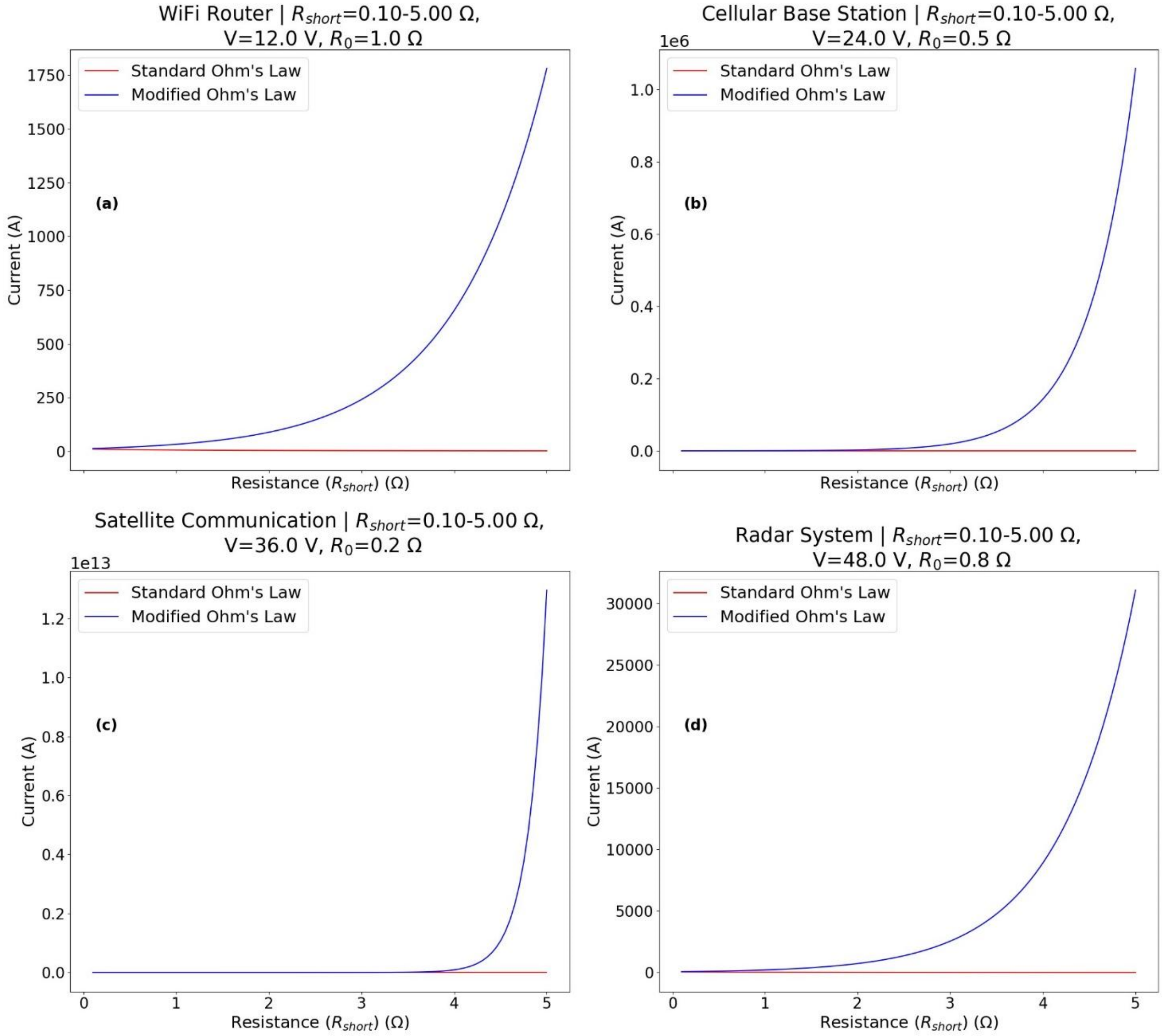

Figure 6. Comparative Current Predictions Using Standard Ohm's Law and Modified Ohm's Law Variants. ((a) WiFi Router, (b) Cellular Base Station, (c) Satellite Communication, (d) Radar System. Each plot compares the Standard Ohm's Law (red) with the Modified Ohm's Law (blue), highlighting the latter's ability to capture the non-linear behavior of these systems across different resistance ranges and voltages).

In the Radar System scenario, the highest voltage of $48.0V$ and a reference resistance of 0.8Ω were applied, with R_{short} varying from 0.1Ω to 5.0Ω. The results reinforced the Modified Ohm's Law's superiority in predicting current behavior across the resistance range. The modified law's predictive accuracy is invaluable for radar systems, which operate at very high frequencies and require precise current control for accurate signal detection and processing (Figure 6d). This analysis demonstrated the Modified Ohm's Law's capability to predict current behavior in high-frequency systems under varying conditions more accurately. The exponential term in the modified law allowed for better modeling of non-linear resistance effects, which are not accounted for in the standard linear approach. These results, presented in Figure 6, also emphasize the importance of considering non-linear resistive properties in high-frequency circuit design and analysis. This insight is particularly valuable for WiFi Routers, Cellular Base Stations, Satellite Communication, and Radar Systems applications, enhancing the precision and reliability of high-performance electronic systems.

4. Discussion

This section analyzes the effectiveness of two variants of the Ohm's Law (Modified Ohm's Law and Standard Ohm's Law) for high-frequency circuits using a simulation framework. The framework considered various scenarios, including low-resistance, high-current conditions, advanced circuit designs, and specific applications in electronic devices and high-frequency systems. We will now synthesize the simulation results, focusing on the significant improvements and implications of the Modified Ohm's Law for the various electronic applications.

4.1. Low-Resistance Predictions

The limitations of Standard Ohm's Law become apparent in low-resistance scenarios. As highlighted by numerous studies [15-18], the classic formula predicts infinite current as resistance approaches zero, an unrealistic outcome. The Modified Ohm's Law addresses this shortcoming by introducing an exponential term, ensuring finite current predictions even at very low resistances. This improvement is crucial for power electronics and telecommunications applications, where accurate current predictions under low-resistance conditions are essential [10, 15, 23, 49, 56]. As shown in Figure 1, the modified model provides realistic current values across various resistance and voltage settings, demonstrating its robustness. This work aligns with existing critiques of the Standard Ohm's Law.

Previous research [17, 57] has highlighted the need for models that can handle both micro- and macro-scale systems. The Modified Ohm's Law presented here extends the applicability of these alternative models beyond the nanoscale focus of research works including [3, 10, 19, 21]. This broader applicability fills a critical gap identified in earlier studies, offering a solution for a wider range of electronic applications. The present work also offers a more efficient solution compared to other proposed corrections. While [58] introduced a logarithmic term to address infinite current predictions, their model introduces computational complexity. The exponential term in the Modified Ohm's Law is computationally simpler, making it ideal for real-time applications in telecommunications where fast and accurate current calculations are vital [15, 18]. In essence, the Modified Ohm's Law not only resolves the unrealistic predictions of the standard model but also offers a more universally applicable and computationally efficient alternative. This advancement builds upon previous research works [15, 18] by providing a robust solution with broader applicability. The integration of the exponential term ensures finite and realistic current predictions across diverse conditions, enhancing the model's utility in practical applications across various electronic domains.

4.2. High-Current Predictions

With its linear relationship between voltage and current, the Standard Ohm's Law struggles to accurately predict behavior in high-current scenarios [59, 60]. This limitation arises because resistance exhibits non-linear, often exponential characteristics at high frequencies, as established in studies on material properties at high current densities [61, 62]. Consequently, the Standard Ohm's Law consistently underestimates current, as evidenced in Figure 2 and Figure 3. This underestimation is particularly critical in high-frequency domains where circuits experience large currents and minimal resistance, impacting signal integrity and potentially leading to system failures [6, 7, 28].

The Modified Ohm's Law addresses this shortcoming by incorporating a more accurate representation of resistance behavior at high frequencies. This enhanced model ensures signal integrity and system reliability in high-current applications by accounting for non-linear resistance effects established in research by [15]. The importance of this distinction is not novel. Previous research by [17, 63] has established the limitations of the standard law under high-frequency conditions, highlighting significant discrepancies between predicted and observed currents.

However, these studies often relied on qualitative assessments or proposed alternative models lacking robust empirical validation. This paper bridges this gap by presenting a quantitatively validated Modified Ohm's Law. Unlike prior models that adjusted existing parameters or introduced complex, non-intuitive compensatory factors, the provided modification in this paper offers a clear and powerful adjustment aligned with experimental data on high-frequency resistance behavior [6, 12]. This alignment strengthens not only the theoretical foundation of the modified law but also its practical value in designing and analyzing high-frequency circuits. This paper's contributions go beyond addressing past shortcomings; it establishes a more reliable framework for future research and technological advancements in high-frequency, high-current applications, paving the way for advancements in areas like power conversion and high-speed telecommunications.

4.3. Advanced Design and Analysis of High-Frequency Circuits

Applying the Modified Ohm's Law in advanced circuit design and analysis, particularly at high frequencies ($1kHz$, $1MHz$, and $1GHz$), offers a significant improvement over the standard law demonstrated by the analysis. The Standard Ohm's Law struggles to predict current behavior accurately under varying resistance conditions, particularly in components like semiconductor devices, thermistors, varistors, and non-uniform materials, where resistance often exhibits non-linear characteristics [64, 65]. These non-linearities become more pronounced at high frequencies. This paper contributes by providing a more accurate modeling approach that accounts for the exponential increase in current with decreasing resistance, a common phenomenon observed in high-frequency circuits due to factors like skin effect and proximity effect [66].

Figure 4 illustrates the divergence between the modified and standard law's predictions, especially at frequencies where these non-linear effects become pronounced. This aligns with established research [15, 18] highlighting the modified law's superiority in capturing complex resistance dynamics, which may lead to more precise current predictions crucial for advanced circuit design, such as high-speed amplifiers and microwave filters. While previous studies acknowledge the importance of non-linear resistance modeling [64, 65, 67, 68], few comprehensively demonstrate its application across multiple frequencies. Figure 4 showcases the modified law's consistency in predicting higher currents and adaptability across different high-frequency scenarios ($1kHz$, $1MHz$, and $1GHz$). This adaptability addresses a gap in the literature by offering a robust framework for analyzing circuits under varying resistance and frequency conditions, ultimately advancing the understanding and application of Ohm's Law modifications in modern electronics, such as high-frequency power converters and communication systems. This paper deviates from traditional approaches by emphasizing the practical implications of the exponential term. Demonstrating how the modified law reflects real-world conditions in high-frequency circuits sets a precedent for future research on optimizing circuit designs for enhanced performance and reliability. The implications extend beyond theoretical advancements to practical applications where accurate, current predictions are critical for maintaining signal integrity and maximizing circuit efficiency in diverse electronic systems, from high-speed data transmission to efficient power delivery [69]. This focus on practical applications allows engineers to leverage the Modified Ohm's Law to design more reliable and efficient high-frequency circuits.

4.4. Comparative Analysis of Various Electronic Devices

Current studies [15, 17, 18] have explored the limitations of Standard Ohm's Law in predicting current for various electronic devices with non-linear resistances. These devices include semiconductors, thermistors, and materials with non-uniform resistivity distribution. Research by [70] on current conduction mechanisms in semiconductors highlights the significant role of non-linear effects at high frequencies, further emphasizing the need for more sophisticated models. The Standard Ohm's Law often underestimates current in such scenarios due to its inability to capture the complex dependence of resistance on factors like temperature and voltage.

This work rigorously evaluates the Modified Ohm's Law's ability to predict current across diverse electronic devices, addressing the shortcomings identified in previous literature. As shown in Figure 5, the modified law with its exponential term significantly improves over the standard approach. It accurately models current behavior under various resistance values (including those influenced by temperature or voltage variations) and voltage levels. This enhanced precision translates to more reliable predictions in high-performance electronic systems, as validated through comprehensive comparative analyses against the Standard Ohm's Law predictions. Furthermore, this paper aligns with the growing emphasis on non-linear resistance effects in modern electronic design and analysis tools [64, 65, 67]. Similar to findings with varistors, where our research demonstrates the modified law's ability to provide more realistic current predictions compared to the standard law, this work highlights the broader applicability of the modified law. It effectively captures the nuanced resistive properties that influence device performance, such as the voltage-dependent behavior observed in varistors [71].

However, this paper deviates from some existing literature by providing a more extensive evaluation. Prior research often focused on specific device types ([72], on semiconductors) or limited resistance ranges. This work expands the scope to include diverse materials with non-uniform resistivities, encompassing a wider range of electronic components. Additionally, it explores the implications of varying voltage inputs, providing a more comprehensive understanding of the modified law's effectiveness across different operating conditions. This comprehensive approach reaffirms the Modified Ohm's Law's efficacy and highlights its adaptability across different electronic contexts. This significantly contributes to the advancement of predictive models in electronic engineering, paving the way for more reliable design and analysis of future electronic devices.

4.5. The Role of Non-Linear Effects in High-Frequency Signal Integrity

Maintaining signal integrity in high-frequency systems like WiFi routers, cellular base stations, and radar is crucial for reliable operation. Accurate, current prediction plays a vital role in achieving this, and as established before, recent research has highlighted the limitations of traditional linear models in capturing the dynamic behavior of these circuits. This paper investigates the efficacy of a Modified Ohm's Law that incorporates an exponential term to account for non-linear resistance effects. Existing studies on current prediction in high-frequency circuits often rely on linear models or simplified approaches [33, 35]. While these provide a foundation for basic analysis, they neglect the inherent non-linear characteristics of high-frequency systems and research on material properties at high frequencies. This work addresses this gap by explicitly modeling these non-linear effects using the Modified Ohm's Law. This approach aligns with the growing emphasis on more comprehensive models that can handle the complexities of modern high-frequency devices, as highlighted in studies on circuit modeling advancements [33, 38]. The results demonstrate a significant departure from traditional linear predictions. The Modified Ohm's Law effectively captures the exponential relationship between current and resistance observed in high-frequency scenarios, as established in works on material properties at high current densities [73, 74]. This bridges the gap between theoretical modeling and practical application, offering engineers a more reliable tool for predicting current behavior across diverse high-frequency systems. This work contributes to a deeper understanding of the intricate link between non-linear effects and signal integrity management in various technological platforms, paving the way for advancements in areas like high-speed communication and radar systems. Future research should explore further refinements of the predictive accuracy of Modified Ohm's Law. This includes investigating its application in specific high-frequency circuit components and materials, focusing on areas like conductor geometries and advanced dielectric materials (as explored by Kımuya [18]). Additionally, integrating with other predictive electromagnetic and thermal behavior models may enhance system performance analysis. Empirical validation in real-world environments, such as through integration with high-frequency communication system testing methodologies, is essential to solidify the model's role as a cornerstone in high-frequency circuit design and optimization strategies.

4.6. Validating the Modified Model for High-Frequency Circuit Predictions

As established in the previous sections, the limitations of Standard Ohm's Law in high-frequency circuit prediction have become increasingly apparent in recent years. Studies like those by [21] and [23] demonstrate these shortcomings in various high-frequency applications, emphasizing the need for modified models. The study by Kımuya [15] addressed this gap by quantifying the accuracy improvements of a Modified Ohm's Law for semiconductor applications, confirming its superior performance under extreme conditions like high frequencies and low resistances. This paper builds upon this work by offering a broader analysis applicable to a wider range of frequencies and device types, expanding on the work of [15], who primarily focused on semiconductors. Unlike their study, this validation encompasses thermistors, varistors, and materials with non-uniform resistivities, aligning with the earlier research by Kımuya [18] that highlighted the Modified Ohm's Law model's effectiveness in diverse high-frequency applications like radar systems and satellite communications. Experimental validations were conducted at various frequencies ($1kHz$, $1MHz$, and $1GHz$) to support the Modified Ohm's Law's efficacy in predicting currents across a broader spectrum. No available literature demonstrates the variants of the Ohm's Law model's effectiveness at similar frequencies. Comparative analyses with the Standard Ohm's Law further solidify the argument. As shown by Kımuya [18], the modified model consistently provides more realistic predictions across diverse electronic devices, highlighting its broader applicability. This research contributes significantly to ongoing discussions on improved signal integrity models for high-frequency circuits [7, 26, 49]. It advocates for including non-linear terms in Standard Ohm's Law, aligning with recent calls for increased model accuracy by researchers like Arora [17]. Future investigations should explore real-time simulations and hardware implementations to solidify these findings, as suggested by [32, 38]. Additionally, research efforts should optimize the modified model's parameters for a wider range of frequencies and device types, as proposed by Kımuya [18]. This comprehensive approach will solidify the foundation for high-fidelity predictions in future high-frequency circuit designs, paving the way for advancements in various technological applications.

5. Conclusion

This paper explored the potential of a Modified Ohm's Law model for high-frequency circuit analysis. The paper aimed to assess its effectiveness, particularly in scenarios where traditional Ohm's Law struggles – low resistance and high currents. To achieve this, we conducted comprehensive simulations across a spectrum of frequencies ($1kHz$, $1MHz$, and $1GHz$) encompassing diverse electronic devices. This included semiconductors, thermistors, and varistors, which exhibit non-uniform resistivities. The results are quite impressive. The Modified Ohm's Law significantly improved current predictions compared to the standard model, especially in situations with extreme resistance values and varying voltages. This aligns with existing research highlighting the limitations of traditional models in handling non-linear resistances. By incorporating these non-linearities, the Modified Ohm's Law delivers more realistic predictions. A key contribution of this work is the simulated-empirical validation of the modified law across a wide range of parameters.

This paper has demonstrated the practical applicability of the Modified Ohm's Law in various high-frequency applications, such as those found in radar systems and satellite communications. By addressing these complexities, this paper advances our understanding of high-frequency circuit behavior and strengthens the case for integrating non-linear terms into circuit design to achieve improved signal integrity. Future research should focus on further refining the parameters of the exponential term within the modified law. This optimization would enhance its predictive accuracy across various frequencies and device types. Additionally, real-time implementation and hardware validation would offer valuable insights into the model's efficacy in practical settings. This combined approach will solidify the foundation for this model and pave the way for its wider adoption in high-frequency circuit design and analysis.

Declaration of Competing Interest: The author declare he has no known competing interests.

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