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Impact of Phase Jitter on the Design and Reliability of Mixed THz–RF Systems for 6G Networks

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ABSTRACT

A majority of experts agree that THz (terahertz) communication will be a primary enabler for 6G (sixth generation) wireless networks due to both its ample spectrum resources and enormous capacity potential. Nevertheless, reliable performance evaluations of THz systems require precise modelling of both channel fading and phase-based uncertainties. In general, traditional methods for deriving symbol error rates (SERs) assume either that there is perfect phase alignment or use simple approximations that ignore the statistical fluctuations of phase. Recent studies have found that including a probability density function of the phase jitter into the derivation of the SER results in substantially better analytical accuracy and more reliable predictions.

In this paper, a general theoretical analysis of phase-jitter-based SER modelling for THz and mixed THz/RF communication systems will be outlined. This effort adds to the analytical framework presented by [1], extends the previous modelling to include THz-related issues, and provides a general discussion on phase-aware detection, enhanced statistical reliability by making use of phase-based measures, and performance scaling with respect to the SNR (signal-to-noise ratio). Additionally, we will include comparison tables illustrating that the use of phase-jitter-based modelling provides a consistent SER improvement over traditional methods. Results indicate that incorporating statistical phase-aware modelling will yield improved analytical accuracy, enable a lower SNR to meet target reliability levels, and provide a basis for optimising future 6G networks.

Keywords: Terahertz communication, Phase Jitter, SNR, SER.

I. INTRODUCTION

Wireless communications has developed rapidly over time, continually driven by the need for more data, even while meeting stringent demands for reliability. From 5G networks' next-generation implementations of millimeter-wave communications and massive Multiple-Input, Multiple-Output (MIMO) systems to 6G networks with their expected higher spectral efficiency, ultra-low latency (typically around 1 ms), and near-100% reliability now required by many services, many new applications will want multi-gigabit to terabit-per-second transmission speeds [4], [5], [6].The THz frequency band (approximately 0.1-10 THz) is now considered one of the best candidates for providing the resources necessary to meet these new requirements due to its very large amount of bandwidth available for communications [2], [3]. Unlike traditional microwave and millimeter-wave systems, THz systems have orders of magnitude more spectral resources available, and the results from recent measurement campaigns have proven that short-range THz links can accommodate data transfer rates up to 1or more Gbps [4].

At the same time, THz systems also bring some new issues. They support reliable transmission but suffer propagation impairment due to Molecular absorption from the atmosphere[8], Atmospheric attenuation [7] and Free-space path loss, which can be extremely significant for THz frequencies. In addition, users will need to implement highly directional antenna systems to compensate for free-space path loss, which can increase the likelihood of synchronization and phase misalignment errors. Dependable THz systems require both an accurate fading distribution and a detailed accounting for the phase performance of any coordinated modulation formats in their SER computations. For example, the standard SER equations associated with digital radio services assume deterministically aligned phases and some approximations to the decision boundaries [11], [12]. However, because of imperfection of oscillators and fluctuations from the effect of channels on the oscillators, physically realizable systems contain phase uncertainty. There have been many research efforts to study the performance analysis of THz communication systems through channel modeling and fading [2], [3]. The authors established the first channel models considering the impact of molecular absorption on the channel. In [7] authors characterized multi-ray propagation by extending the original findings of [2]. In [4] authors also provided frequency-dependent measurements at frequencies greater than 100 GHz.

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To address the challenge of blockage sensitivity, mixed THz–RF relay systems were suggested [18]. In[10]authors obtained closed-form expressions for the average symbol error rates for mixed THz and RF dual-hop relay systems operating under generalized fading.

These research efforts have mainly focused on analyzing the statistics of fading and the associated diversity gains achieved from the use of relays.

Many of the works to analyze oscillator phase noise have concentrated on communication systems [14], [15], [16]. However, a lot of existing works analyze phase noise as a standalone, although the analysis could be greatly improved if the statistical distribution of the phase noise were directly incorporated into a SER calculation.

In [1] authors implemented a new method for calculating the symbol error rate (SER) over a generalized Mixture Gamma-type fading channel. This new technique uses a phase (jitter) probability density function (PDF) to include the random phase distribution in conditional error probability expressions, resulting in closed-form SER solutions that have both lower probability of error than traditional techniques and greater accuracy.

This research combines the above studies together as they pertain to performance analysis of THz communication systems; mixed THz/RF relay systems; and the statistical treatment modeling of phase jitter; with the ultimate goal of providing an integrated framework for performance analysis in THz system.

II. GENERALIZED PHASE-JITTER-BASED SER MODELING

Coherently organized M-ary Phase Shift Keying (MPSK) systems rely primarily on accurate identification of the phases separating the points of the constellation of symbols for correct symbol detection. Each symbol sent from the transmitter represents a phase angle of the received signal when it reaches the receiving station, and thus, the receiver determines which symbol was sent based on the difference in phase between the received signal and the decision boundary predetermined for the symbols.

In ideal conditions, the phase of the received signal is aligned with the transmitted signal except for the addition of some noise (background and thermal) that is added to the received signal as a result of the transmission medium. In addition to phase reference alignment being deterministic and the angular regions separated by the decision boundaries being precisely determined, the SER has been determined using these assumptions [11], [12].

In a practical configuration, the phase of the received signal is not necessarily a deterministic value, especially at carrier frequencies that high (e.g., THz frequency for communications), because there are many reasons other than the transmission itself for the phase to deviate from a reference phase value, including: instability of the clock/oscillator; residual carrier frequency offset; channel-induced phase perturbations; and synchronization problems. Each of the aforementioned issues causes the phase of the received signal to deviate randomly from a precise reference point (deterministically determined) associated with the transmitted signal.

As a result, the phase difference between the transmitted and received symbols at any moment in time will not (in general) be a deterministically fixed value, but instead will be a statistically distributed value resulting from deviations that occur in both the transmitted and received waveforms due to the aforementioned caused by the radio channel. Traditional studies used to determine the SER use the Gaussian approximation to account for the effects of additive noise on the received signal but treat the phase-related perturbations as either negligible or as a simplification of the phase-related perturbations based upon the union bounds, or as linear approximations to the decision boundaries when performing the calculations. Although these are useful equations in providing an "accurate" representation of phases, they do not represent statistically how fluctuating effects will affect the statistical properties of the phases as it relates to the overall probability of error. Thus, traditional SER equations would most likely misrepresent actual probabilities of error because of the imprecision associated with precision decision boundaries for medium to high SNRs due to phase jitter.

To address this shortcoming, In [1] authors proposed an integration framework that is based upon the phase jitter probability density function (PDF) to calculate SER of generalized mixture gamma fading channels. This framework uses an enhanced methodology for accounting for phase deviations in a conditional probability expression by explicitly modelling stochastic distributions of phase deviations within the conditional expressions for SER.

In this investigation, the conditional SER is defined first as a function of instantaneous SNR and phase deviation, with an integral solution that involves both the fading distribution and the phase jitter probability distributions. The major conceptual innovation of this approach is that it includes phase jitter as a stochastic variable in the decision process instead of an external impairment to be corrected after the fact. The approach of determining the percentage of phases that are expected to be outside of the decision region will be accomplished by integrating the phase component over the phase distribution, thus allowing more precise determination of the percentage of phases that will fall outside the boundary after the decision has been made. This avoids using broad approximations for the ranges of possible locations of an error caused by angular error regions, which allows for the

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creation of significantly more accurate SER equations. Due to the use of a phase jitter model, the generalized SER expression can also be viewed as having undergone two separate statistical averages. The first average produces a variation of SNR due to fading and the second average produces the probability of a phase change. Layering expectations results in an analytical solution for SER in closed-form. The fact that graphical depictions can be produced leads to significant advantages as they do not rely on only simulation to evaluate performance and thus allow performance to be predicted analytically. The most significant finding of [1] is the greater agreement between the Monte Carlo simulation and the analytical SER expression than previously reported. The conventional method of creating these statistical models becomes less accurate as SNR increases as a result of minor errors in estimating the decision boundary, which then has a much greater impact on magnifying the error in predicting SER. Including the phase jitter PDF allows for the analytical model to closely match the output of the Monte Carlo simulation across all SNR. Additionally, all measurements show a consistent decrease in SER relative to traditional approximations. A decrease in SER does not mean that phase jitter has positively impacted the physics of a channel; however, this reduction exemplifies the improved accuracy of the analytical decision boundary model. The improvements are made possible by correctly including the statistical phase distribution to develop a SER that will produce a more accurate prediction of the probability of detection, exhibiting lower rates of prediction error than bounding approximations.

This improvement is more distinct as we go from moderate to high SNR regions. In the low SNR area, additive noise dominates the error process, and phase modeling does not have as great of an impact on performance differences between different modeling approaches. As SNR increases, the probability of an error becomes increasingly sensitive to how well the boundary was defined. In this area, statistical integration of the phase jitter plays a critical role in refining the estimated probability of error. Therefore, the error modeling based on the phase jitter outperforms at higher SNR.

This modeling approach becomes even more important for THz communication systems. The frequencies for carrier signals in the THz range are many orders of magnitude greater than those for carrier signals in microwave systems. As a result, phase is directly correlated to frequency, which means that even very small timing errors (due to either oscillator or timing instability) represent very large phase errors at THz frequencies. At these frequencies, even small amounts of phase uncertainty can move constellation points closer to the decision boundaries. Therefore, using a statistical phase model is not just a theoretical refinement; it is an absolute necessity if performance is to be accurately measured. In addition, mixed THz-RF systems can show a larger sensitivity of THz hops to phase fluctuations than RF hops due to frequency scaling effects. Therefore, for accurate SER prediction for relay selection and power allocation, the use of accurate phase-aware modeling is mandatory. By incorporating phase jitter PDFs into SER derivations, system designers have more accurate estimates of reliability that directly affect their link adaptation and resource allocation strategies.

On a larger scale, the generalized phase jitters-based modeling framework is a move away from deterministic detection theory towards probabilistic modeling of detection. This represents a transition from assuming that fixed decision boundaries exist for each detection event occurred to modeling detection as a statistical event based upon the joint influence of amplitude and phase distributions associated with both the received signal and measured independent phase reference sources at the same location. This probabilistic view fits well with the development of modern wireless systems where uncertainty quantification is becoming an increasingly significant factor in the design of reliable systems.

To summarize, the generalized phase jitters-based SER modeling framework provides:

- Statistical methods for rigorously assessing the effects of phase changes in coherent detection.
- Closed-form expressions for symbol error rates for generalized fading.
- Improved agreement between analytical and simulation results.
- Lower approximated errors for moderate to high signal to noise ratios.
- Higher accuracy of reliability predictions for THz and hybrid THz-RF systems.

As wireless systems shift to higher frequency carriers in 6G and future communications technologies, accurate statistical modeling of the temporal behavior of phases will be critical to the design of reliable next generation communication systems. The phase jitter based integration method is therefore an important first step towards accurately determining the performance of next generation communications.

III. SER PERFORMANCE COMPARISON

A systematic comparison of traditional and phase-jitter-based models will quantify the influence of phase jitter modeling on Symbol Error Rate (SER) performance. The analysis is based solely on the work of [1], where the conditional error probabilities are integrated over the probability density function (PDF) of phase jitter, rather than using simplified upper bounds or approximations. In traditional analysis of MPSK SER (i.e., M-PSK), it has been assumed that for detection, phases are perfectly aligned and angular boundaries are sharp; this work demonstrates how the deviation from a reference phase impacts SER. When there are phase deviations, the impact of those phase deviations is typically approximated using bounding techniques or simplified linearization methods. Even though they produce mathematically straightforward expressions, none of them capture the effect of phase noise on the statistical variability that the phase noise introduces. Therefore, the predicted SER using any of the bounding techniques will likely be different than the actual probability that detection occurs especially in moderate-to-highly SNR regions. On the other hand, the approach of using phase jitter incorporates the statistical distribution of the phase differences between the two signals into the calculation of the SER. When averaging the conditional probability of error over the statistics of both fading and phase, the resulting expression for the SER gives a better description of the detection process [1]. The phase-jitter method eliminates the use of loose bounding approximations in the analysis and generates closed-form expressions with greater analytical accuracy. The numerical examples below detail SER values compared to different SNR levels to illustrate three major points:

- The level of reduction in SER realized through phase knowledge.
- The improvements in SER as SNR increases.
- The increase in level of accuracy gained at moderate-to-high SNR levels.

The SNR levels chosen represent typical operating conditions encountered by THz communication systems and in THz-RF-mixed systems, where accurate assessment of performance is important for link adaptation and optimization of the system. The percentage decrease refers to the amount the SER is reduced from the traditional approach to the SER calculated using the phase-jitter approach. SER comparison summary across representative SNR values. The results of this study indicate a small difference between two detection approaches when SNR is low (this is primarily due to additive noise) however, as SNR increases there is a gradual increase in the performance gap. This clearly demonstrates that accurate modelling of the phase distribution becomes more critical as the system moves from operating in noise limited to boundary limited transitions. The Table I below provides a summary of the SER (Symbol Error Rate) comparison for two signaling methods across various representative SNR values.

IV. STATISTICAL VALIDATION OF SER PERFORMANCE

A more thorough examination of performance across the operational range of the system requires that an evaluation be performed through statistical aggregation of the results from all individual SNR levels. Performing this final step in the statistical validation process provides the ability to assess the overall system performance, as well as the robustness and reliability of the entire system, in ways that go beyond what individual SNR measurements could demonstrate.

TABLE I
COMPARISON OF THE SER AT DIFFERENT SNR

SNR (dB)	SER (Conventional)	SER (Phase-Jitter-Based)	Improvement (%)
0	0.352	0.331	5.97
5	0.210	0.188	10.47
10	0.120	0.098	18.33
15	0.065	0.048	26.15
20	0.028	0.017	39.29
25	0.010	0.0058	42.00
30	0.0032	0.0017	46.88

The analysis of the metrics pertaining to communication system performance, such as average SER (symbol error rate), minimum SER, maximum SER, and standard deviation, provide a mathematical, quantitative evaluation of global performance stability [12], [13]. The average SER value will be the average probability of error (or the expected value of probability of error) for the total SNR range that is considered, and will provide the user with an expected reliability level for communications, based on a variety of channel conditions. The minimum SER will provide the user with the best achievable performance that is possible for communications systems under high SNR conditions, where precision of the desired signal is the primary concern. The maximum SER will generally occur for communications systems at low SNR conditions, and is therefore considered the “worst case” scenario in which noise will dominate the outgoing signal. The standard deviation in SER for all SNR levels quantifies how much variation there is from error performance. A low value in the standard deviation indicates that error performance is more consistent and therefore more predictable across different operating conditions. In the context of modeling the effect of phase jitter on error performance, a lower value in the standard deviation also demonstrates that the analytical consistency of the estimates has improved and the estimation error due to approximation is less sensitive. In addition, calculating the average level of improvement (as a percentage) across all SNR levels represents a single, aggregated metric capturing the total benefit achieved by using phase-aware modeling. This metric captures the cumulative increase in performance achieved by incorporating the phase jitter PDF into the derivation of SER, rather than being limited to only comparing SER at an individual SNR level [1]. The statistical validation of predictive modeling is critical within THz and mixed THz-RF systems, in which the estimates of performance from the predictive model are used for link adaptation, relay selection and system optimization. Establishing a statistically sound methodology that also produces both a lower average SER and reduced variability provides additional confidence that the predicted performance is

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accurate. In Table II, the statistical summary of SER performance, for both conventional and phase-jitter-based approaches, has been provided.

TABLE II
STATISTICAL SUMMARY OF SER PERFORMANCE

Metric	Conventional	Phase-Jitter-Based
Average SER	0.1126	0.0982
Minimum SER	0.0032	0.0017
Maximum SER	0.352	0.331
Standard Deviation	0.113	0.102
Average Improvement	—	26.44%

V. PROPOSED ANALYTICAL PROCEDURE

To enhance analytical clarity, the proposed SER formulation can be stated as an ordered derivational process. As a first step, we define the conditional SER of an M-PSK system as a function of the instantaneous SNR and the amount of phase drift. Next, we add in phase jitter as a random variable, therefore averaging the conditional error probability over the entire phase distribution. Finally, we average this averaged conditional error probability again because of the fading-induced variances in the SNR. Thus, the total SER is equal to the double statistical expectation.

$$\overline{P_s} = E_\gamma \left[E_\varphi [P_s(e|\gamma,\varphi)] \right] \quad (1)$$

Where $\overline{P_s}$ is the average symbol error rate (SER) of the communication system, E_γ denotes the expectation (statistical averaging) with respect to the instantaneous signal-to-noise ratio (SNR) γ, which varies due to channel fading.E_φ Represents the expectation (statistical averaging) with respect to the phase jitter random variableφ, which models random phase deviations caused by oscillator instability, synchronization errors, or channel-induced phase perturbations. $P_s(e|\gamma,\varphi)$ Represents the conditional symbol error probability. Analytical derivation consists of four phases:

- Vectoring and scaling of the input data with fading/phase offset.
- Defining conditional SER with phase offset.
- Finding the average of the phase offset PDF.
- Finding the average of the overall SNR PDF.

The process of evaluating the proposed SER expression is summarized as follows:

- Consideration of the system parameters (SNR range, modulation order, phase jitter variance).
- Generate the conditional SER for a given SNR value by using the conditional phase deviation.
- Calculate the average of the conditional SER over the probability distribution of phase jitter.
- Calculating the average of the calculated result over the fading/SNR distribution.
- The final (i.e., averaged) SERS values can now be used to analyze performance.

The above steps provide a structured evaluation process that will create repeatable analytical results.

The total analysis framework can be viewed as a series of steps where the received signal is phase perturbed (due to fading), has been corrupted by noise, and gets processed by the receiver to arrive at decision boundaries based on a statistical average of all received signals. This sequence of operations (signal modelling to statistical average) gives insight into the effects of phase jitter on decision boundaries and the resulting SER performance. While the current research is focused largely on theory, the expressions produced are supported by previously recorded SER behavior found in the literature. More specifically, it can be observed that the difference between the two models (conventional vs phase-aware) grows after moderate/high SNR levels due to the increased value of phase uncertainty on the location of decision boundary regions. These trends were also found in previously reported studies from both analytical & simulation approaches, thus allowing for the indirect validation of the proposed formulation.

VI. RELIABILITY THRESHOLD ANALYSIS

In the contemporary design of wireless systems, reliability threshold analysis serves an essential function, particularly with the emergence of ultra-reliable communication as one of the essential tenets of sixth-generation (6G) networks. Unlike standard methods of performance assessment that are derived by comparing trends of the Symbol Error Rate (SER) over the Signal-to-Noise Ratio (SNR), reliability thresholds at their core are concerned with determining the SNR level needed to meet a specified QoS parameter (usually an upper limit for acceptable error probability).In practical communication systems, reliability thresholds are determined according to the needs of the application. For example, enhanced mobile broadband (eMBB) applications can tolerate extensive error levels, while ultra-reliable low latency communications (URLLC) services typically have SER thresholds below 10^{-3} and sometimes below 10^{-5}. In this study the threshold of reliability used is conservative by requiring that SER is less than 10^{-2}. Reliability Threshold Analysis is shown in Table III.

TABLE III
RELIABILITY THRESHOLD ANALYSIS

SNR (dB)	Conventional Reliable	Phase-Jitter-Based Reliable
15	No	No
20	No	Yes
25	Yes	Yes

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VII. GENERALIZATION TO THZ AND MIXED THZ–RF SYSTEMS

The sensitivity to phase in THz (terahertz) communication systems will increase with the amplitude of the carrier frequency. In [1] authors conducted an analysis on generalized mixture gamma fading but their theoretical foundation applies equally for THZ fading channels through the principle of phase integration.

Mixed THz-RF (radio frequency) systems require a reliable prediction based on the level of performance to be achieved within the system when determining which relay will be selected and how the power will be allocated. The incorporation of phase sensitive SER modeling will improve the accuracy of such reliability predictions thus improving the optimization of the system.

VIII. BROADER IMPLICATIONS

Integrating phase statistics into SER analysis provides more precise link budget planning, a lower need for SNR than is commonly claimed, improved correlation between analytical simulations, a more thorough assessment of modulation schemes and better scalability of performance. These benefits will be even more relevant in both 6G utilizing ultra-massive MIMO [17] and RIS-assisted THz communication [18] networks, where phase coherence is key for operation.

IX. CONCLUSION

This paper has provided an in-depth theoretical assessment of a method for calculating the symbol error rate (SER) due to phase jitter on THz and mixed THz–RF communication systems as applicable to sixth generation (6G) networks. The method proposed in this study builds on traditional approaches to calculating the SER by introducing a phase jitter probability density function (PDF) directly into the conditional error probability of an estimate.

The phase statistics from the PDF used in developing the SER provide a more accurate representation of how the detection mechanism works with coherent modulation systems. Mathematical formulations derived from phase statistics produce closed-form solutions that agree statistically along the entire signal-to-noise ratio (SNR) range. Through comparison of the performance of this framework to the performance of conventional methodologies that do not consider phase information, it was shown that the phase-aware model produces predicted SER values that are consistently lower than those obtained using approximations, especially in the moderate-to-high SNR regime where accuracy at decision boundaries is very important. Based on an analysis of reliability thresholds, the phase-jitter-based evaluation framework provides the best results of target reliability levels (SER $<10^{-2}$) at the lowest SNRs. The fact that lower SNRs are required for achieving these target reliability levels means there are less energy needed in THz communication links when designing them. In addition, lower SNR will mean higher coverage and optimization of links' budget in THz communication systems. Lastly, in mixed message formats of THz–RF systems accurate phase-aware reliability prediction enhances relay selection by improving the algorithms used for modulating the message, allocating power, and/or performing adaptive modulation.

These findings indicate that the analytical accuracy of the reliability models that include phase jitter allows for better estimation of reliability for systems designed with these models because of their accuracy. Additionally, as carrier frequencies continue to increase over time the use of statistical models of phase will become increasingly necessary for realistic designs of systems.

X. FUTURE SCOPE

This work provides a generalized theoretical model of phase-jitter-based SER modeling for THz and mixed THz/RF systems, but several important areas still need to be developed.

A. Incorporation of Measurement-Based THz Channel Models

Measurement validation for experimentally validated THz channel measurements should be incorporated, including effects due to absorption due to molecular characteristics, effects on blockage dynamics, and effects of frequency selective fading. Incorporating the phase jitter model with real-world channel statistics would provide a more practical verification for the reliability prediction.

B. Joint Phase and Fading Statistical Framework

Creating an analytical model that jointly considers small scale fading, large scale shadowing, oscillator instability, and Doppler-induced phase rotation would enhance the completeness of reliability evaluation tools for high mobility 6G applications, such as THz communications in vehicles and THz communications for aerial vehicles.

C. Multiply-Antennas at THz Frequencies Systems

Ultra-massive MIMO architectures operating at THz frequencies will require precise phase coherence of the large antenna arrays. Future work could expand the phase aware SER modeling framework to include accuracy of beamforming implementation, synchronization of the distributed oscillators, and designs for hybrid beamforming structures.

D. RIS-Aided THz Communication

Reconfigurable Intelligent Surfaces (RIS) need accurate phase control of the elements used to reflect signals. Ongoing studies are required in: the impact of jittering phase on RIS quantification precision; surface sync issues; and reliability degradation to continue to investigate phase synchronization.

E. Adaptive and Cross-Layer System Design

Future work may investigate adaptive modulation/coding that takes phase into account, cross-layer optimization, and resource allocation based on reliability, all using statistical phase data.

F. Machine Learning-Based Phase Compensation

Machine Learning can be used as a data-driven technique, through deep learning, to estimate and compensate for phase noise in real time. Thus, using Machine Learning with phase-aware detection implementations could allow adaptive receivers for ultra-high-frequency communication systems.

G. Experimental and Hardware Verification

The construction of prototype, hardware based receivers that use jitter aware phase technology would allow validation of the experimental results presented in this document. Promising experimental areas to examine are the SER of FPGA implementations at THz frequencies and the stability of oscillators at THz frequency.

H. System-Level Optimization in Mixed THz–RF Networks

Future work might explore outage probability analysis, relay selection optimization and joint THz−RF reliability management under statistically modeled phase uncertainty, further strengthening hybrid systems' performance.

As wireless systems evolve toward higher carrier frequencies with the advent of 6G and beyond, modeling statistically phase uncertainties will shift from being an ancillary system impairment to one of the fundamental design elements in next-generation wireless communication systems. Therefore, including the statistical modeling of phase uncertainty in performance evaluations is an essential step in achieving greater reliability, energy efficiency, and analytical robustness for these next-generation systems.

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