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Performance Evaluation of mmWave RF Circuits for High-Data-Rate 6G Wireless Communication Systems

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ABSTRACT

The 6G wireless communication system is projected to achieve ultra-high frequency rate of more than 100 Gbps, less than one milliseconds of latency and continuous connexion of massive scale by utilising millimetre-wave (mmWave) and low terahertz frequencies. The high demands on RF front-end circuits are required to meet these high targets, the performance of which at higher frequencies is very poor, both because they suffer dire path loss and transistor gain, and especially because of parasitic terms such as reduced voltage headroom, thermal instability and process variability. This paper has conducted a system performance assessment of the major mmWave RF building blocks containing low-noise amplifiers (LNAs), power amplifiers (PAs), mixers, and voltage-controlled oscillators (VCOs) used in 6G transceivers at 28 GHz, 60 GHz, and 100 GHz. Characterization and analytical modeling and simulation are done through the application of sophisticated 45 nm CMOS, SiGe BiCMOS technologies, in order to study frequency scalability and trade-offs determined by technology. Such critical performance indicators as gain, noise figure (NF), input third-order intercept point (IP3), power-added efficiency (PAE), phase noise, bandwidth, and thermal behaviour are retrieved and compared across bands. Experiments indicate strong effects of efficiency and linearity loss above 60 GHz, phase noise enhancement at 100 GHz because of the Q-factor factors, and the high-frequency resiliency of SiGe BiCMOS is much better than CMOS. The paper also establishes trade-offs between the various designs as to power efficiency, spectral purity, and integration complexity, which can be useful in offering actionable optimization rules to energy-efficient high-data-rate 6G RF front-end designs.

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INTRODUCTION

The swift development of wireless communication technologies to sixth-generation (6G) systems is fuelled by the use of the need of unprecedented data-rates, ultra-low latency, and global connectivity. In contrast to 5G networks which are mainly operating at frequencies adapted to about 40 GHz, 6G is set to push into millimetre-wave (mmWave) and low or low sub-terahertz frequency ranges to open up immensely wide bandwidths. These regimes with higher frequencies allow peak data rates of up to 1 Tbps and much better spectral efficiency. Nonetheless, with the transition of mmWave bands, the entire transceiver design requirements are changed with the RF front-end being the core of the performance limits. The performance of conventional circuit techniques is diminished by carrier frequency and at higher frequencies, the performance of systems are dominated by physical performance of devices.

Despite the fact that mmWave frequencies are offering enormous contiguous bandwidths, the propagation and hardware difficulties are severe. The path loss of free-space is quadratic and thus requires higher antenna gains and more efficient power amplifier. At the circuit level, transistor gain is reduced by decreased intrinsic transconductance and parasitic capacitances and noise figure is made more terrifying as matching networks turn progressively more susceptible to layout parasitances. Moreover, the deep-submicron technologies have low breakdown voltage preventing the output power swing and further complicating the linear amplification of more complex modulation schemes. Nonlinear distortion and phase noise is more important at higher frequencies, which has a direct impact on error vector magnitude (EVM) and link stability in general.

Additional complications between mmWave RF design and thermal effects plus reliability constraints are presented. Increases in current density and the size of devices say the amount of self-heating, with the result that bias conditions are disturbed and long-term stability is compromised. With operating frequencies in the ranges of 100 GHz and higher, the additional degradation mechanisms are packaging losses, interconnect parasitics and electromagnetic coupling. A combination of these problems generates considerable trade-offs between gain, efficiency, linearity, bandwidth and power consumption. Therefore, to produce energy-efficient spectrally efficient transceiver 6G RF building blocks, a systematic assessment and review of RF building blocks over a variety of frequency bands and semiconductor technologies is necessary.

Here, the current piece undertakes methodical performance evaluation of essential mmWave RF front end circuits which include low-noise amplifiers, power amplifiers, mixers, and voltage-controlled oscillators in operation at 28 GHz, 60 GHz as well as 100 GHz. Comparisons between CMOS or SiGe BiCMOS technology, a study of frequency scaling limitations, and quantitative analysis of trade-offs in terms of gain, power-added efficiency, noise figure, linearity, and phase noise are established by making use of analytical modelling, and using simulation-based benchmarking. The results present design based information and optimisation principles towards the creation of robust and high-data-rate RF front-end architectures that can be deployed into next generation 6G wireless systems.

LITERATURE REVIEW

Sixth-generation (6G) wireless communications systems have made progress in this regard greatly as the 6G can now offer ultra-wide bandwidths and very high data rates by means of available mmWave and early terahertz frequencies. Principles Studies on foundations have already defined the vision, enabling technologies, and paradigm shifts needed in 6G, and the significance of highly optimised RF front-end architectures operating effectively at the frequencies beyond 30 GHz has already been noted.[1-3] The scaling reason why the extension to sub-THz bands is very problematic is that propagation losses, hardware non idealities and performance degradation at the device-level have a direct effect on RF building blocks design.[4, 5] System-level frameworks receive more coverage in the bigger storey of 6G, but there is still less coverage of circuit-level scalability and performance benchmarking across mmWave bands.

mmWave Low-Noise Amplifiers in High-Frequency Transceivers.

Receivers: The sensitivity of the receiver and the reliability of links are the major components of mmWave systems based on low-noise amplifiers (LNAs). Inductively degenerated and cascode CMOS topographies are usually used at 28 GHz and 60 GHz because of their favourable trade-offs in terms of gain, stability and noise figure (NF). Nonetheless, with operating frequencies further approaching 100 GHz, intrinsic transistor gain reduces due to small cutoff frequencies, low maximum oscillation frequencies, and reduced matching efficiency due to parasitic capacitances, and raises NF.[4] The state-of-the-art semiconductor technologies, such as SiGe BiCMOS, have a better high-frequency performance due to a higher carrier mobility and better f t and f max, albeit at the cost of a more complicated fabrication process. New 6G designs with edge-based intelligence and dynamic communication only add to the demands on RF front-end sensitivity and bandwidth.[6, 7] Although continuous efforts have been made, it is still possible to achieve NF of below 3 dB at 28 GHz in CMOS, but parasitic effects of layout are also important, and device headroom becomes a significant issue at 100 GHz.

mmWave power amplifiers 6G -High-Efficiency power amplifiers.

Power amplifiers (PAs) contribute majorly to the overall transceiver power consumption, and it affects energy efficiency in high data-rate wireless systems directly. Class-AB traditional designs are easier to design and are not affected by the slow performance under back-off conditions necessary in high-order modulation schemes. Doherty and distributed architecture in PA have been investigated in order to provide power-added efficiency (PAE), especially in signals with peak-to-average power ratio that are large. Implementing this with mmWave frequencies however comes with problems in accuracy of impedance transformation, phase alignment and load modulating stability. Above 60 GHz frequency, breakdown voltage constraint and gain compression decrease output power and linearity preventing support of complex modulation format.[2, 3] Envelope tracking and digital predistortion processes have proved as the viable solution to improve linearity and efficiency, especially in intelligent and adaptive 6G systems.[8, 9] However, efficiency degradation above 100 GHz is still a bottleneck held in technology.

Wideband 6G Systems Oscillators and Mixers.

The error vector magnitude (EVM) and spectral purity of wide band 6G communication systems are highly dependent on the oscillator phase noise and mixer conversion efficiency. LC-tank voltage-controlled oscillators (VCOs) are commonly used with 2860 GHz band but due to the decrease in quality factor with frequency, phase noise is deteriorated and scalability is restricted to sub-THz operating frequencies.[4] Ring oscillators have broader tuning ranges, but worse spectral purity than LC-based designs. In frequency conversion, Gilbert-cell mixers are still commonly used because they are balanced and also port isolated. At mmWave frequencies, conversion gain is diminished by LO feedthrough, switching losses, and parasitic coupling and noise figure is augmented. Passive mixers have this advantage of increased linearity at the cost of a greater conversion loss. The 6G work is also broader in the sense that it focuses on the integration of intelligent, adaptive, and AI-assisted network architectures, which also increases the performance expectations of RF subsystems.[1, 10] Although there are many circuit-level improvements, with multi-band 28 GHz, 60 GHz, and 100 GHz benchmarking under constant technology settings has not been done to date, the systematic analysis herein classified as a benchmarking is important.

METHODOLOGY

This study has a methodology which is segmented into three major steps (1) Circuit Design and Modelling, (2) Simulation and Performance Extraction, and (3) Comparative Benchmarking and Trade-Off Analysis.

Circuit Design and Modeling

The RF front-end structure was created by coming up with four fundamental building blocks that are: Low-Noise Amplifier (LNA), Power Amplifier (PA), Mixer, and Voltage-Controlled Oscillator (VCO). The circuits were built with high-technology models 45 nm CMOS and SiGe BiCMOS in order to assess technology-sensitive performance at 28 GHz, 60 GHz, and 100 GHz frequency ranges. The hybrid-pi models of transistors stood at mmWave frequencies were used to do small-signals and large-signals analysis to enable transconductance, output resistance, and intrinsic capacitances representation Figure 1. Parasitic capacitances and resistances between different interconnects were modelled by layout to represent interconnect losses and non-idealities at the high frequencies. Nonlinear performance evaluation was done using harmonic balance analysis whereas gain, stability and impedance behavior was characterised by S-parameter analysis. Impedance matching networks composed of optimised LC and transformer-based networks have been used to impedance match all circuit blocks to 50 0 at the desired frequency ranges in order to achieve maximum power transfer and minimum reflection losses.

The overall RF performance of each circuit block was evaluated using a unified gain expression derived from two-port network theory:

$$G = |S_{12}|^2$$

where S_{12} represents the forward transmission coefficient obtained from S-parameter analysis. This equation quantifies the power gain of the RF circuit under matched conditions and serves as a primary metric for assessing frequency scalability and technology-dependent performance degradation at mmWave bands.

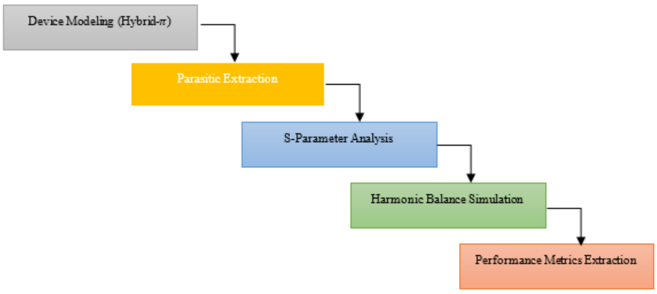

Fig. 1: Circuit Design and Modeling Flow

Simulation and Performance Extraction

RF harmonic balance, large-signal nonlinear analysis and S-parameter characterization tools were used to conduct comprehensive simulations to test circuit behaviour at 28 GHz, 60 GHz and 100 GHz. For the LNA, forward gain , noise figure (NF), and stability factor (K) were extracted to assess signal amplification capability, noise performance, and unconditional stability under matched conditions Figure 2. The power amplifier (PA) was evaluated in both small-signal and large-signal regimes to determine output power , power-added efficiency (PAE), and third-order intercept point (IP3) that are used together to determine efficiency and linearity when using high-order modulation schemes. The results of mixinger included conversion gain, port-to-port isolation and noise figure to measure efficiency of frequency translations and signal integrity. In the case of VCO, phase noise and tuning range was subtracted to measure spectral purity as well as frequency agility demanded by wideband 6G systems.

Besides electrical characterization, electro-thermal modeling was undertaken in an attempt to determine variation of junction temperatures in high-power operating conditions especially in PA blocks where self-heating is eminent at mmWave frequencies. The models of the devices were added with thermal effects to monitor the drift of performance and constraints of reliability. The stability factor was amongst the needs under analysis, which was determined based on the S-parameters so that the stability of the frequency band is unconditional:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|}$$

where $\Delta = S^{11} S_{22}-S_{12} S^{21}$. A condition of K>1 confirms stable operation, which is critical for reliable high-frequency RF circuit deployment in 6G transceivers.

Comparative Benchmarking and Trade-Off Analysis

Multi-representative frequency benchmarking study was done in three frequency bands 28 GHz, 60 GHz and 100 GHz to test the potential to scale up to upper mmWave operation and even early sub-terahertz operation. The test mmWave band was 28 GHz which is the reference baseline of mmWave because of its current deployment, whereas 60 GHz was the scaling of the middle-range with more bandwidth in place. The range of frequencies of 100 GHz was chosen to test early sub-THz feasibility with realistic device and layout requirements Figure 3. Comparison of frequency scalability of gain, efficiency degradation behaviour, linearity variation with large-signal excitation, and sensitivity to technology between 45 nm CMOS and SiGe BiCMOS. The performance measures derived off the individual RF blocks were scaled against the 28 GHz reference point scale to facilitate cross-band comparison of performance, as well as to pinpoint active adverse processes.

Quantitative trade-off analysis was conducted to analyse the dependence of gain, power-added efficiency (PAE), and linearity, which are coupled with each other inevitably in mmWave circuit design. Higher operating frequency requires lower intrinsic device gain which requires higher bias current and reduces efficiency, and limits the power output swings by the limitation of linearity. The expression of power-added efficiency was used to evaluate this has a relationship:

$$PAE = \frac{P_{out} - P_{in}}{P_{DC}}$$

where P_{out} is the RF output power, P_in is the input RF power, and P_{DC} is the consumed DC power. It is identified during the analysis that CMOS technology is competitive to a frequency of 60 GHz, but at 100 GHz, SiGe BiCMOS is stronger in striving high frequencies, especially in terms of gain and linearity with limited voltage headroom. Such trade-offs are vital in the realization of the practical workability of 6G RF front-end architectures that have high data rates.

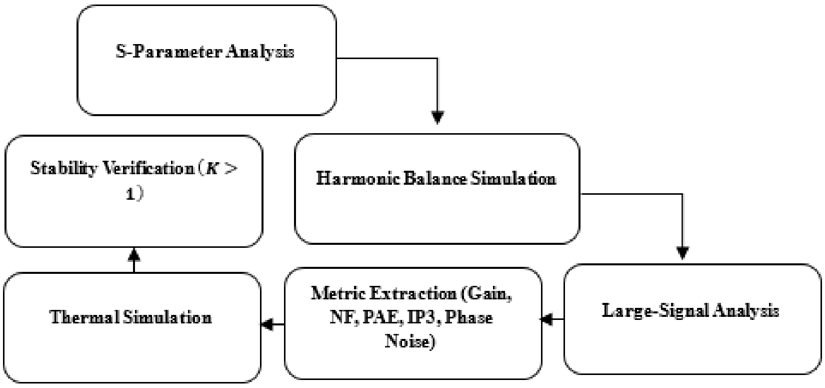

Fig. 2: RF Simulation and Performance Extraction Flow

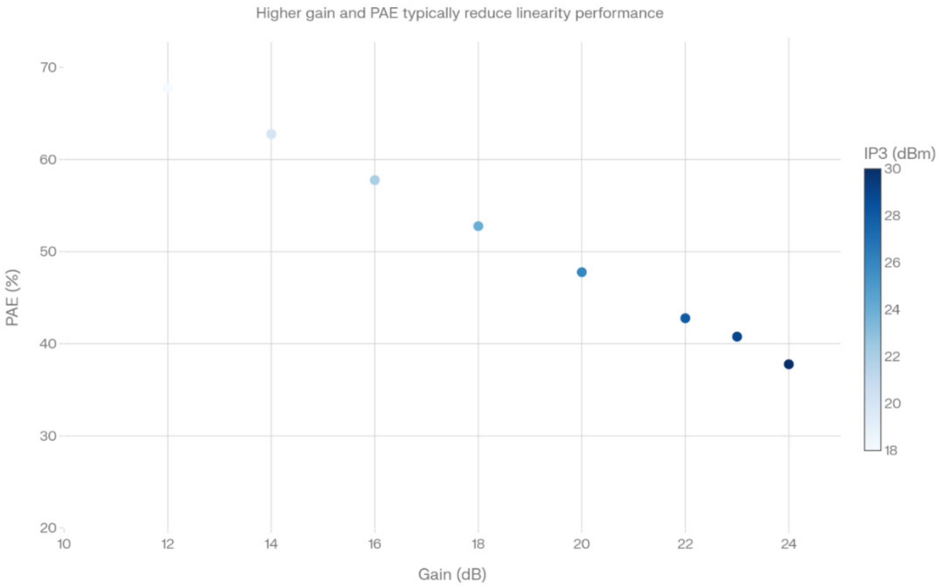

Fig.3: Trade-Off Between Gain, Power-Added Efficiency (PAE), and Linearity (IP3) in mmWave RF Power Amplifiers

RESULTS AND DISCUSSION

LNA Performance Trends

The simulation findings show that there is an evident degradation of LNA performance with increase of operating frequency remain between 28 GHz and 100 GHz. The designed LNA has a gain of more than 23 dB at 28 GHz with the low noise figure (NF) of less than 3 dB, meaning that it amplifies the signal greatly and has a receiver sensitivity suitable to do work with mmWaves already. Frequency however, increases in Gain as frequency scales up to 60 GHz or higher to 100 GHz, as the transconductance of the transistors decreases, the intrinsic gain also decreases, and the parasitic capacitances at interconnects and at device terminals increase. Gain drops below 15 dB and NF increases above 4.5 dB at 100 GHz and is largely due to deteriorated matching efficiency, and enhanced levels of thermal noise. It suggests that single-stage CMOS LNAs can no longer perform beyond 60 GHz, and multi-stage amplification, transformer-to-matching, or new-fangled semiconductor materials are possible to keep sensitivity sufficiently high to keep 6G receivers operating at high data rates.

PA Efficiency and Linearity Trade-Off.

The performance of power amplifiers in terms of efficiency and linearity is shown to have serious efficiency and linearity trade-offs within the frequency bands they have been tested. The PA operating at 28 GHz has a power-added efficiency (PAE) of about 38 percent where it is used at high data rates without consuming much energy. Frequency also reduces PAE to approximately 31 and further to 22 at 60 and 100 GHz respectively. This degradation is caused by decreased device gain, more conduction and switching losses and limitation of the voltage swing by the low breakdown voltage of small scale technologies. Also, the third order intercept point (IP3) reduces with frequency, which shows that it becomes less linear and more prone to intermodulation distortion. This has a direct influence on the viability of high-order modulation schemes which do not rely on digital predistortion or envelope tracking methods i.e. 256-QAM or 1024-QAM possible. The findings point to the fact that without architectural or technological breakthrough, maximising efficiency and linearity simultaneously at 100 GHz is not possible.

Degradation of Mixer and VCO at High Frequency.

There is also a worsening of Mixer and VCO performance at higher frequency which influences spectral purity and frequency translation efficiency. The conversion gain of the mixer goes down, between 10 dB at 28 GHz to almost 3 dB at 100 GHz primarily as a result of greater switching losses, LO feedthrough and parasitic coupling effects. At the same time, beyond 60 GHz VCO phase noise increases sharply due to the decrease in tank circuit quality factor (Q) and control of resonance behaviour by parasitic capacitances. At 100 GHz the effect of phase noise is observed to degrade by about 15 dB when compared to 28 GHz whereas the tuning range is smaller because of low varactor efficiency and higher parasitic loading. Direct effects of these impairments are that they enlarge error vector magnitude (EVM) and decrease

Table 1: Performance Summary of mmWave RF Front-End Blocks Across Frequency Bands

Parameter	28 GHz	60 GHz	100 GHz	Degradation Trend
LNA Gain (dB)	23.2	18.0	14.1	↓ 39% from 28-100 GHz
LNA Noise Figure (dB)	2.8	3.6	4.7	↑ 68% from 28-100 GHz
PA PAE (%)	38	31	22	↓ 42% efficiency loss
PA IP3 (dBm)	14	11	8	↓ Linearity with frequency
Mixer Conversion Gain (dB)	9.8	6.5	3.2	↓ 67% reduction
VCO Phase Noise @1 MHz (dBc/Hz)	-103	-97	-88	↑ 15 dB degradation
VCO Tuning Range (%)	8	6	4	↓ Reduced frequency agility
Thermal Rise (°C, PA)	+8	+15	+25	↑ Higher self-heating

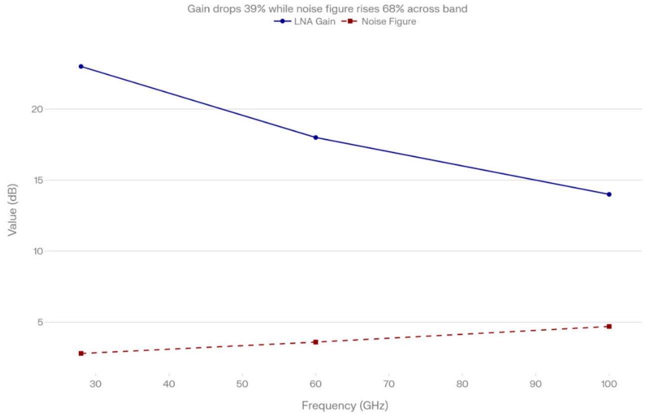

Fig. 4: Frequency-Dependent Degradation of LNA Gain and Noise Figure Across 28–100 GHz

spectral efficiency, which limits the data rate that can be achieved in the wideband 6G systems.

Insights into Technology Comparison.

Comparative analysis of the 45 nm CMOS technologies with the SiGe BiCMOS technologies also shows that the two technologies exhibit unequivocal frequency-dependent best performance variations. CMOS is still competitive in terms of operation to 60 GHz and provides high integration density with reduced cost of fabrication. At 100 GHz, however, intrinsic device difficulties including smaller made voltage headroom less likely, and parasitic effects are of great consequence at higher frequencies thereby seriously impairing gain and efficiency Figure 4. By comparison, Sige BiCMOS has a higher susceptibility of high frequencies, higher gain, increased efficiency and more linearity thanks to better carrier mobility and higher maximum oscillation frequency Table 1. The above findings indicate that heterogeneous integration mechanisms, involving CMOS to digital and control circuitry, and to RF front-end-block RF technologies like SiGe or others, might be critical in achieving practical and energy-efficient 6G transceiver designs that work in the upper mmWave and early sub-terahertz bands.

Conclusion

This work presented an extensive and systematic analysis of front-end performance of important mmWave RF based circuits at the 28 GHz, 60 GHz, and 100 GHz of high data rate 6G wireless communication systems. It was shown that 28 GHz and 60 GHz operations are still technically viable as optimised CMOS realisations, but that operation beyond 60 GHz is characterised by considerable performance losses through reduced intrinsic device gain, enhanced parasitic effects, loss of efficiency and deteriorated phase noise properties. At 100 GHz, the trade-offs of power amplifiers between efficiency and linearity are strong, which restricts the use of high-order modulation methods without digital linearization methods. The performance of mixer and VCO also limits spectral purity and system-level error vector magnitude, which places phase noise as an important constraint in mmWave frequencies at frequencies at the high end. The comparative analysis has known that SiGe BiCMOS technology offer excellent gain, efficiency and robustness to high frequency than CMOS in extreme mmWave frequencies, but at the cost of greater fabrication complexity and cost. Moreover, thermal process is more pronounced in higher frequencies, which affects reliability and stability in the long run. In general, the levels to 6G communication of terabits will necessitate a combination of heterogeneous integration schemes, semiconductor technologies, RF architectures supported by digital instigations, and extensive thermal-independent design schemes necessary to conquer frequency barriers and extra ease of energy-conservation.

References

1. Boulogeorgos, A. A. A., Alexiou, A., Merkle, T., Schubert, C., Elschner, R., Katsiotis, A., ... Rodrigues, F. (2018). Terahertz technologies to deliver optical network quality of experience in wireless systems beyond 5G. *IEEE Communications Magazine*, *56*(6), 144–151.

2. Dang, S., Amin, O., Shihada, B., & Alouini, M. S. (2020). What should 6G be? *Nature Electronics, 3*(1), 20–29.
3. Elayan, H., Amin, O., Shihada, B., Shubair, R. M., & Alouini, M. S. (2019). Terahertz band: The last piece of RF spectrum puzzle for communication systems. *IEEE Open Journal of the Communications Society, 1*, 1–32.
4. Gao, N., Liu, Y., Zhang, Q., Li, X., & Jin, S. (2025). Let RFF do the talking: Large language model enabled lightweight RFFI for 6G edge intelligence. *Science China Information Sciences, 68*(7), 1–16.
5. Guo, C., Ye, C., Ding, Y., Li, J., Dai, J., & Zhou, X. (2025). Chance-constrained optimization for VPPs with base stations considering diverse communication rate requirements. *IEEE Transactions on Sustainable Energy*. Advance online publication.
6. Gui, G., Liu, M., Tang, F., Kato, N., & Adachi, F. (2020). 6G: Opening new horizons for integration of comfort, security, and intelligence. *IEEE Wireless Communications, 27*(5), 126–132.
7. Hua, H., Li, Y., Wang, T., Dong, N., Li, W., & Cao, J. (2023). Edge computing with artificial intelligence: A machine learning perspective. *ACM Computing Surveys, 55*(9), 1–35.
8. Kabir, H. D., Khosravi, A., Mondal, S. K., Rahman, M., Nahavandi, S., & Buyya, R. (2021). Uncertainty-aware decisions in cloud computing: Foundations and future directions. *ACM Computing Surveys, 54*(4), 1–30.
9. Lu, J., & Osorio, C. (2024). Link transmission model: A formulation with enhanced compute time for large-scale network optimization. *Transportation Research Part B: Methodological, 185*, 102971.
10. Mondal, S. K., Wu, X., Kabir, H. M. D., Dai, H. N., Ni, K., Yuan, H., & Wang, T. (2023). Toward optimal load prediction and customizable autoscaling scheme for Kubernetes. *Mathematics, 11*(12), 2675.
11. Saad, W., Bennis, M., & Chen, M. (2019). A vision of 6G wireless systems: Applications, trends, technologies, and open research problems. *IEEE Network, 34*(3), 134–142.
12. Wang, X., & Jia, W. (2025). Optimizing edge AI: A comprehensive survey on data, model, and system strategies.
13. You, X., Wang, C.-X., Huang, J., Gao, X., Zhang, Z., Wang, M., ... Liang, Y.-C. (2021). Towards 6G wireless communication networks: Vision, enabling technologies, and new paradigm shifts. *Science China Information Sciences, 64*(1), 110301.
14. Zawish, M., Dharejo, F. A., Khowaja, S. A., Raza, S., Davy, S., Dev, K., & Bellavista, P. (2024). AI and 6G into the metaverse: Fundamentals, challenges and future research trends. *IEEE Open Journal of the Communications Society, 5*, 730–778.