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Article

Noise Analysis in 5G Network Transmission Systems

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ABSTRACT

The advancement of 5G networks offers high speed communication, low latency, and massive connectivity, but faces significant challenges from noise and interference in both the sub 6 GHz and millimeter wave (mmWave) bands. This study aims to analyze the characteristics and dominance of noise in 5G transmission systems and to evaluate efficient mitigation strategies such as adaptive beamforming. As a review article rather than an experimental study, the work synthesizes findings from a broad body of literature on 5G noise and interference, with the goal of providing a consolidated state of the art overview. Because a robust survey of 5G noise dynamics typically requires 50–100 or more relevant sources, the current scope is intentionally treated as a targeted, thematically focused review rather than a fully exhaustive global survey. The analysis therefore emphasizes key trends—such as the shift from thermal noise limited to interference limited conditions in mmWave networks under dense deployments and highlights how dynamic noise mitigation through techniques like beamforming can improve spectral efficiency and reliability in 5G rollout, including in Indonesia's 5G deployment context.

1. Introduction

The development of 5G network technology has become the main foundation for supporting high-speed, low-latency communications and massive connectivity in various critical applications such as the Internet of Things (IoT), autonomous vehicles, Ultra-Reliable Low-Latency Communication (URLLC), and Enhanced Mobile Broadband (eMBB). The use of sub-6 GHz and millimeter-wave (mmWave) frequency bands enables greater data capacity, but also introduces significant signal propagation challenges due to more severe path loss and fading at high frequencies (Rappaport et al., 2019; Rebato et al., 2016). This phenomenon is further complicated by the integration of satellite-based non-terrestrial networks (NTNs), which extend network coverage but are vulnerable to variations in atmospheric conditions and high mobility (Dahlman et al., 2020; Fokin et al., 2023).

The characteristics of noise and interference in 5G transmission systems are a major concern because they can degrade overall signal quality, especially in OFDM systems that are sensitive to phase noise at mmWave frequencies, causing inter-carrier interference and bit error rate degradation (Santacruz et al., 2021; Rappaport et al., 2019). Previous research has shown that in mmWave networks, noise-limited conditions dominate in low-density areas, while interference-limited conditions emerge in ultra-dense deployments, influenced by beamforming and base station density (Rebato et al., 2016; Björnson et al., 2021). Furthermore, thermal noise remains a major factor in the sub-6 GHz band, particularly in low signal-to-noise ratio scenarios, requiring optimized resource allocation to maintain reliability (Dahlman et al., 2020; Parkvall et al., 2022).

This problem is further exacerbated by the lack of comprehensive studies comparing noise dynamics across different frequency bands and network architectures, making it difficult to design mitigation strategies that adapt to dynamic conditions such as urban user density or NTN integration (Fokin et al., 2023; Santacruz et al., 2021). Most previous literature tends to isolate the analysis of phase noise or multi-user interference without a multi-dimensional comparative approach, leaving gaps in the holistic understanding of interference

dominance across deployment scenarios (Rebato et al., 2016; Dahlman et al., 2020). Consequently, 5G system design is often suboptimal, particularly in anticipating the trade-off between spectral efficiency and transmission reliability in heterogeneous environments.

This study aims to analyze the characteristics and dominance of noise in 5G transmission systems in the sub-6 GHz and mmWave bands, as well as evaluate the most efficient mitigation strategies such as adaptive beamforming and power management. The urgency of this research lies in the urgent need to optimize 5G networks in Indonesia to support national digital transformation, where noise can hamper large-scale commercial rollout (Wang et al., 2021; Ghosh et al., 2022). The novelty of this study is a multi-dimensional comparative approach that consolidates global case studies with the latest 3GPP data, offering contextual recommendations not yet available in previous literature (Fokin et al., 2023; Rappaport et al., 2019).

2. Literature Review

The investigation of noise and interference in 5G networks has drawn significant attention in recent years, especially with the increasing deployment of sub 6 GHz and millimeter wave (mmWave) bands. In mmWave scenarios, Rebato et al. (2016) demonstrated that 5G cellular networks in the 28 GHz band can transition from noise limited to interference limited regimes as base station density increases, highlighting the critical role of sectorization and beamforming in shaping interference patterns. This work provides a foundational analytical model for understanding how blockage limited propagation and directional antennas affect the signal to interference plus noise ratio (SINR) in ultra dense deployments.

Parallel to this, 3GPP technical specifications have formalized the system level design of noise and interference management in New Radio (NR). 3GPP (2018) specified NR physical channels and modulation (Release 15), which underpin the 5G NR waveform and numerology, while 3GPP (2022) extended these to Release 17 with enhanced physical layer mechanisms for interference aware scheduling and power control. These standards provide the technical framework for adaptive beamforming

and dynamic resource allocation, which are central to mitigating thermal and inter user interference in sub 6 GHz bands.

On the sub 6 GHz side, Parkvall et al. (2018) and Parkvall et al. (2022) describe the NR access technology that supports both eMBB and IoT oriented services, emphasizing spectral efficiency and robustness against low SINR conditions caused by thermal noise and dense multi user environments. Dahlman et al. (2018, 2020) further detail how 5G NR handles interference through flexible numerology, advanced multi antenna schemes, and power control mechanisms, showing that interference aware scheduling can significantly improve fairness and throughput in urban deployments.

In the mmWave domain, phase noise and hardware related impairments become increasingly important. Santacruz et al. (2021) analyzed phase noise in mm Wave OFDM analog radio over fiber (ARoF) systems for beyond 5G, demonstrating that local oscillator phase noise can severely degrade bit error rate performance and that digital compensation techniques can mitigate this effect. Similarly, a study by Santacruz et al. (2020) on phase noise in mm Wave OFDM systems for 5G showed that phase noise induced inter carrier interference is highly sensitive to oscillator quality and subcarrier spacing, suggesting that low phase noise clocks and pilot based compensation are essential for high order modulation schemes.

Interference modeling in ultra dense mmWave deployments has also been studied from a stochastic geometry perspective. Björnson et al. (2016) and Björnson et al. (2021) analyzed massive MIMO networks and showed that while spatial multiplexing can improve spectral efficiency, intra cell interference and beam misalignment become limiting factors when base station density rises. Fokin et al. (2023) proposed a practical model for interference evaluation in 5G mm Wave scenarios that accounts for directional beam patterns, blockage, and user mobility, demonstrating that interference limited conditions dominate in dense urban topologies.

Another important dimension is the integration of non terrestrial networks (NTNs) and satellite based backhaul links. Fokin et al. (2023) and other works on NTN 5G convergence highlight that atmospheric attenuation, Doppler shifts, and high mobility

links introduce additional noise and interference sources that are not captured by conventional terrestrial models. Rappaport et al. (2019) emphasized that above 100 GHz propagation is highly sensitive to molecular absorption and rain fading, further complicating noise characterization in mmWave backhauled 5G infrastructures.

Finally, several survey style contributions have consolidated these findings into broader taxonomies of 5G noise and interference. For example, Wang et al. (2018) reviewed 5G cellular architectures and key enabling technologies, including massive MIMO, mmWave, and dense small cells, and discussed how these elements interact with noise and interference budgets. Ghosh et al. (2019, 2022) updated this perspective beyond Release 15, showing that 5G evolution toward 5G Advanced and 6G will require even more sophisticated interference mitigation schemes, including AI driven resource allocation and self organizing networks.

Collectively, this body of literature confirms that 5G noise dynamics are highly band and deployment dependent: thermal and inter user noise dominate in sub 6 GHz, while mmWave networks shift toward interference limited and phase noise limited regimes, especially in dense urban or ultra dense small cell deployments. These studies also highlight that adaptive beamforming, power management, and advanced physical layer signal processing are essential tools for mitigating noise and improving spectral efficiency and reliability in 5G transmission systems.

3. Research Methodology

This research method is qualitative, employing an in-depth literature analysis approach to secondary data, enabling a comprehensive exploration of noise characteristics in 5G network transmission systems without the need for primary experiments. This approach was chosen because it is suitable for integrating findings from scientific literature, 3GPP technical standards, and industry reports, as recommended in qualitative research methodologies that emphasize the synthesis of existing data to generate a holistic understanding (Sugiyono, 2021; Creswell & Poth, 2022; Rebato et al., 2016; Dahlman et al., 2020). This secondary

analysis method is effective in the telecommunications sector, where data from global case studies can be systematically compared to identify noise interference patterns in the sub-6 GHz and mmWave bands.

The research instruments included secondary documents such as reputable scientific journals from Google Scholar, 3GPP Release 15-17 specifications, and 5G implementation reports from various countries, collected through a systematic search using keywords such as "5G noise analysis" and "mmWave interference." Data analysis techniques involved thematic grouping for noise types (thermal, phase, inter-user), quantitative-qualitative comparison of their impact on system performance, and comparative interpretation using source triangulation, as outlined in the qualitative content analysis procedure (Emzir, 2021; Sudaryono, 2023; Santacruz et al., 2021; Fokin et al., 2023). This technique ensured validity by cross-verifying findings from primary sources such as Rappaport et al. (2019) with current 3GPP data.

The study population consisted of all scientific publications, technical standards, and 5G implementation case studies published between 2016 and 2025, with a focus on Google Scholar-indexed articles discussing noise and interference in 5G networks. A purposive sample of 20–25 relevant primary sources was selected, including noise-limited studies on mmWave (Rebato et al., 2016), OFDM phase noise (Santacruz et al., 2021), and ultra-dense interference models (Fokin et al., 2023), as well as standard methodological references to meet inclusion criteria such as having an active DOI and high relevance (Sugiyono, 2021; Creswell & Poth, 2022).

The research procedure was carried out in stages: the first stage was data collection through a search of the Google Scholar database and the 3GPP website; the second stage involved literature analysis to classify noise based on frequency bands; the third stage compared case studies of 5G deployments in developed countries; and the final stage was the synthesis of mitigation recommendations through a comparative matrix (Sudaryono, 2023; Emzir, 2021; Dahlman et al., 2020; Rappaport et al., 2019). This procedure followed a logical flow from description to interpretation, ensuring the

reliability of the results for 5G network development in the Indonesian context.

4. Results and Discussion

Secondary data analysis revealed findings concerning the characteristics of transmission noise interference in 5G network subsystems. The data analyzed included academic journals, 5G technical standards, telecommunications industry reports, and case studies of 5G network implementations from various countries. The analysis focused on the characteristics of 5G networks in the sub-6 GHz and millimeter wave (mmWave) frequency bands.

The analysis revealed that in the sub-6 GHz band, the main disturbances affecting transmission system performance are thermal noise and inter-user interference. These conditions are influenced by user density and limited available spectrum, making radio resource management a critical factor in maintaining service quality. This finding aligns with the characteristics of 5G networks designed for eMBB services and massive machine-type communications in dense urban environments. In the mmWave frequency band, the study findings indicate differences in interference characteristics compared to the sub-6 GHz band.

Data shows that high-frequency transmission systems are highly sensitive to propagation conditions, base station density, and the direction in which the signal is directed. In low- to medium-density networks, transmission system performance tends to be hampered by internal system noise, so improvements in communication quality are largely dependent on improved hardware and signal processing techniques. However, in high-density or ultra-dense scenarios, intra-cell interference becomes dominant and can mitigate signal interference and noise. Analysis has shown that without effective interference management, increasing network density does not necessarily result in a proportional increase in system performance.

This situation also indicates a shift in the dominant interference, from noise to interference in 5G mmWave networks. The use of signal-steering techniques such as beamforming plays a crucial role in controlling the level of interference in 5G transmission systems. Enhanced or precise beamforming can amplify the desired signal and reduce interference. Thus, transmission quality can be

maintained. However, imperfect beam alignment can increase disruptive interference and reduce system reliability, especially with highly directional mmWave frequencies. Furthermore, analysis of 5G technical specifications shows that interference mitigation mechanisms have been designed considering both noise and interference in physical and MAC layer mitigation through mechanisms such as power management and adaptive bandwidth allocation. However, the effectiveness of these mechanisms largely depends on the implementation scenario and network environment.

Noise interference conditions in 5G network signal transmission systems are sometimes dynamic and depend on the combination of frequency bands, network density, and signal processing techniques. Therefore, designing an adequate 5G network requires a comprehensive approach that considers all technical and environmental aspects, as well as network management strategies.

5. Conclusion

This study concludes that noise in 5G network transmission systems is dynamic, with thermal noise and inter-user interference dominating the sub-6 GHz band due to spectrum limitations and urban user density, while in mmWave, phase noise and intra-cell interference are the main factors that shift from noise-limited to interference-limited as base station density increases (Rebato et al., 2016; Dahlman et al., 2020). These findings emphasize the importance of adaptive beamforming and power management to mitigate interference, thereby improving the spectral efficiency and reliability of eMBB and URLLC services. Practical implications include recommendations for 5G network design in Indonesia that integrate these strategies to support national digital transformation.

However, the study's limitations lie in its reliance on secondary data without primary experimental validation, which may limit generalizability to local conditions such as tropical topography or Indonesia's specific NTN interference (Santacruz et al., 2021; Fokin et al., 2023). Suggestions for future research include ray-tracing-based simulations or hybrid field testing to measure noise in real time in ultra-

dense deployments, as well as exploring AI-driven mitigation for heterogeneous scenarios.

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