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A Study on Packet Error Rate in Wi-Fi Networks

Pala, M. Maqbool*[1], and Ajaz Ahmad Lone[2]

[1]*Department of Computer Applications, Government Degree College, Bhaderwah, Jammu and Kashmir, India*
[2]*Department of Education, Government Degree College, Chenani, Jammu and Kashmir, India*

Corresponding author: **Pala, M. Maqbool** | E-mail: **palahredu@gmail.com**

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Abstract
Wireless Fidelity (Wi-Fi) has become one of the most widely used technologies for providing wireless Internet access in homes, enterprises, educational institutions, and public spaces. The performance of Wi-Fi networks is influenced by several factors, among which Packet Error Rate (PER) is a dominant one. PER measures the ratio of transmitted packets that are received incorrectly due to channel impairments, interference, noise, and network congestion [9]. A high PER can significantly impact or reduce network throughput, increase latency, and reduce the Quality of Service (QoS) experienced by users. Modulation and Coding techniques necessary for both measurement and mitigation are also included. This paper presents a comprehensive study of Packet Error Rate in Wi-Fi networks, analysing its causes, impact on network performance, measurement techniques, and techniques to mitigate the error rate. The study also discusses the relationship between PER, Signal-to-Noise Ratio (SNR), modulation schemes, and transmission distance. The findings would prove helpful to work out new designs for optimizing Wi-Fi network performance and reliability.

Keywords: *Wi-Fi Networks, Packet Error Rate, SNR, Throughput, IEEE 802.11, Network Performance.*

I. Introduction
Wireless Local Area Networks (WLANs) based on the IEEE 802.11be and 802.11ax standards have become most frequently used components of modern communication systems. The increasing demand for high-speed wireless connectivity has led to the development of advanced technologies such as IEEE 802.11ac, 802.11ax, and IEEE 802.11be to cater to the increasing demand of its usage [6]. Despite all these technological developments, wireless communication still remains susceptible to transmission errors caused by environmental conditions like EM interference, Noise, bad weather conditions that hamper wireless communication and hardware limitations. Packet Error Rate (PER) is one of the primary metrics used to evaluate the reliability and efficiency of wireless communication systems [9]. PER represents the ratio of incorrectly received packets to the total number of transmitted packets. Understanding PER is essential because packet errors lead to retransmissions, increased bandwidth consumption, temporal delays and reduced overall network performance. This paper investigates the factors affecting PER in Wi-Fi networks and explores methods that decrease PER and improves throughput.

II. Background and Related Work
The IEEE 802.11 family of standards defines the physical medium access control (MAC) layers for WLAN communications [2,3,4].

Various studies have examined the relationship between channel quality, channel type and packet transmission success [2].
Research has shown that PER is influenced by:
1. Signal-to-Noise Ratio (SNR)
2. Bit Error Rate (BER)
3. Channel fading
4. Co-channel interference
5. Network congestion
6. Modulation

Most researchers, including A. Goldsmith T. S. Rappaport, E. Perahia and R. Stacey have suggested the usage of adaptive rate control algorithms that dynamically adjust transmission parameters to minimize packet losses and improve throughput. Secure and protected networks are, as always, very important

III. Packet Error Rate in Wi-Fi Networks
A. Definition of Packet Error Rate
In a Wi-Fi network, the Packet Error Rate (PER) is defined mathematically as the ratio of incorrectly received data packets to the total number of transmitted packets.
Incorrect packets / Total number of transmitted packets
\(\text{PER}=\frac{N_{\text{error}}}{N_{\text{transmitted}}}\)
Where \(N_{\text{error}}\) is the number of packets received with at least one uncorrectable bit error, and \(N_{\text{transmitted}}\) is the total number of sent packets.

At a physical and link layer level, PER is dictated by the Bit Error Rate (BER), the size of the packet (N), and the channel characteristics.

1. Fundamental Mathematical Relationship (Independent Bit Errors)

Assuming a simplified Additive White Gaussian Noise (AWGN) channel where bit errors occur completely independently of each other, a packet is considered successful only if all of its bits are transmitted without error.

If a packet contains (N) bits and the probability of a single bit error is (P_{b}) (the Bit Error Rate), the probability of transmitting a single bit successfully is ($1 - P_b$). Therefore, the probability of transmitting the entire packet successfully (P_{success}) is:

$$P_{\text{success}}=(1-P_{b})^{N}$$

Because a packet is in error if even one bit fails, the Packet Error Rate is therefore complemented of a successful transmission:

$$\text{PER}=1-P_{\text{success}}=1-(1-P_{b})^{N}$$

Linear Approximation

For highly reliable links where the BER is exceptionally small ($P_b \ll 1$), the expression can be simplified using the binomial approximation:

$$\text{PER}\approx N\times P_{b}$$

2. Factoring in Modulation (The Role of SNR)

The Bit Error Rate (P_{b}) itself is not constant; it depends on the Signal-to-Noise Ratio (SNR) and the Modulation and Coding Scheme (MCS) selected by the Wi-Fi protocol. For example, if a Wi-Fi link drops to a basic modulation scheme like BPSK (Binary Phase Shift Keying) due to distance, the bit error probability is defined via the complementary error function (erfc):

$$P_{b}=\frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_{b}}{N_{0}}}\right)$$

Where $\frac{E_{b}}{N_{0}}$ is the energy per bit to noise power spectral density ratio (closely tied to SNR). Substituting this back into our PER equation reveals how the physical environment impacts packet success:

$$\text{PER}=1-\left(1-\frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_{b}}{N_{0}}}\right)\right)^{N}$$

As the Wi-Fi user moves farther away or encounters interference, SNR drops, P_{b} increases exponentially, and the PER surges toward 1.0 (100% loss).

3. Real-World Wi-Fi Complexity: Channel Coding

Modern Wi-Fi systems (such as Wi-Fi 6, 7) do not transmit raw bits; they protect packets using Forward Error Correction (FEC) codes like Convolutional Codes or Low-Density Parity-Check (LDPC) codes.

FEC allows the receiver to locate and fix a limited number of errored bits within a block. The result is that, bit errors at the output of the decoder are no longer independent—they arrive in tight clusters called error bursts. To present this mathematically, professionals rely on the Symbol Error Rate (P_{s}) or the First-Event Error Probability (P_{f}) of the decoder:

$$\text{PER}\le 1-(1-P_{f})^{L}$$

Where L is the number of decoding blocks or symbols within the Wi-Fi packet payload.

B. Relationship Between BER and PER

Packet Error Rate is closely related to Bit Error Rate (BER). Assuming independent bit errors:

$$PER = 1 - (1 - BER)^{L}$$

Where:

- BER = Bit Error Rate
- (L) = Packet length in bits

With an increase in packet size, PER increases.

IV. Factors Affecting Packet Error Rate

A. Signal-to-Noise Ratio (SNR)

SNR represents the ratio between the desired signal power and background noise power. Higher SNR values generally result in lower PER and vice-versa because packets can be decoded more accurately [7,8].

B. Distance Between Transmitter and Receiver

Like in almost all bounded media barring OFC as distance increases, signal attenuation occurs due to path loss. Lower received signal strength increases the probability of packet errors.

C. Interference

Wi-Fi networks often operate in crowded frequency bands, particularly the 2.4 GHz spectrum. Sources of interference include:

- Neighbouring Wi-Fi networks
- Bluetooth devices
- Microwave ovens
- Wireless cameras
- IoT devices

Interference increases packet corruption and PER.

D. Multipath Fading

Indoor environments create reflections from walls, furniture, and obstacles. Multiple copies of the same signal arrive at different times, causing fading, redundancy, and packet errors.

E. Network Congestion

A large number of simultaneous users may cause collisions and retransmissions, increasing packet losses and reducing network efficiency.

F. Modulation and Coding Scheme

Higher-order modulation schemes such as 64-QAM and 256-QAM provide higher data rates but require stronger signal quality. Under poor channel conditions, increased PER may be experienced.

V. Impact of Packet Error Rate on Network Performance

A. Throughput Reduction

High PER results in frequent retransmissions, reducing effective throughput and wasting bandwidth [5].

B. Increased Latency

Retransmission mechanisms introduce delays, which negatively affect real-time applications such as video conferencing, real-time transactions and online gaming.

C. Energy Consumption

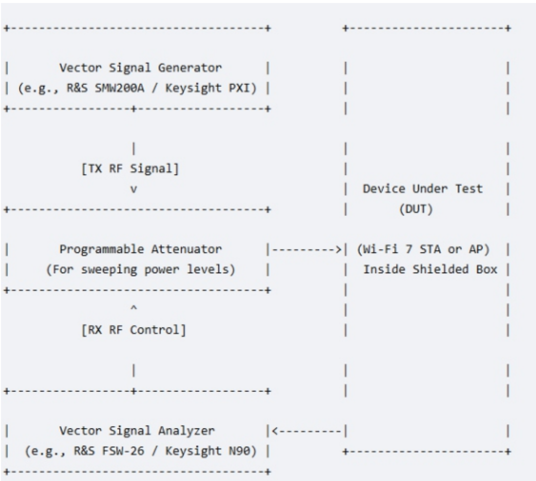
Wireless devices consume additional energy when failed packets are re-transmitted, reducing battery life in mobile devices.

D. Quality of Service Degradation

Applications requiring low latency and high reliability, such as Voice over IP (VoIP) and video streaming, are particularly sensitive to packet errors.

VI. Measurement & Evaluation of PER

Measurement setup for Packet Error Rate (PER) on Wi-Fi 7 (IEEE 802.11be) needs a conducted RF signalling test architecture to isolate and quantify receiver sensitivity. Because Wi-Fi 7 introduces ultra-wide 320 MHz channels, 4096-QAM modulation, and Multi-Link Operation (MLO), the hardware chain meets incredibly strict linearized and synchronized points. This testing needs a network emulator that can present real-world conditions to the Device Under Test (DUT). The Keysight wireless connectivity test platform emulates hundreds of clients, tests the performance of 160 MHz Wi-Fi 6E and 320 MHz Wi-Fi 7 channels with 4x4 multiple-input, multiple-output (MIMO), and evaluates interworking between cellular and Wi-Fi. The test solution includes analysis to provide Phy / MAC-level information such as rate versus range, enhanced Rx sensitivity, radio unit (RU) sweep analysis, and full-rate throughput to generate relevant Wi-Fi signalling and RF throughput results.



A. Practical Setup

A typical PER evaluation setup consists of:

- Wi-Fi access point
- Wireless client device
- Traffic generator
- Packet analyser.
- Signal monitoring tools

Controlled experiments can be performed under varying distances, transmission powers, and interference levels [8].

B. Measurement Procedure

1. Transmit a known number of packets.
2. Record successfully received packets.
3. Identify corrupted or lost packets.
4. Calculate PER using the standard formula.

C. Example Calculation

To calculate the Packet Error Rate (PER), consider a standard Wi-Fi scenario with independent bit errors.

Scenario Parameters

- **Packet Size:** 1,500 bytes (a standard Wi-Fi Ethernet frame MTU)
- **Bit Error Rate (BER or P_{b}):** 1×10^{-5} (meaning 1 out of every 100,000 transmitted bits encounters an error due to the current SNR and modulation scheme)

Step-by-Step Calculation

Step 1: Convert Packet Size from Bytes to Bits (N)

Since the Bit Error Rate is applied to individual bits, convert the packet size into total bits: $\text{Total\ Bits\ }(N)=1500\text{\ bytes}\times 8\text{\ bits/byte}=\mathbf{12,000}\text{\ bits}$

Step 2: Use the Exact PER Formula

The mathematical equation assuming independent bit errors is:

$\text{PER}=1-(1-P_{b})^{N}$

Substitute the values into the equation: $\text{PER}=1-(1-0.00001)^{12000}$

$\text{PER}=1-(0.99999)^{12000}$

Using precise exponential calculation: $(0.99999)^{12000}\approx 0.88692$

Subtracting this from 1 gives: $\text{PER}=1-0.88692=\mathbf{0.11308}\text{\ (or\ }\mathbf{11.31\%}$)

Result: In this network environment, approximately 11.31% of all transmitted packets will arrive with an uncorrectable error and require retransmission which is appreciably high.

Alternative: Using the Linear Approximation

When the BER (P_{b}) is small, use the quick linear approximation method ($\text{PER} \approx N \times P_b$):

$\text{PER} \approx 12,000 \times 0.00001=\mathbf{0.12}\text{\ (or\ }\mathbf{12\%}$)

VII. Techniques for Reducing Packet Error Rate

A. Adaptive Modulation and Coding

Modern Wi-Fi systems dynamically adjust modulation schemes based on channel quality to minimize packet errors [2].

B. Error Correction Coding

Forward Error Correction (FEC) techniques enable receivers to recover certain corrupted bits without retransmission.

C. Channel Selection

Selecting less congested channels reduces interference and lowers PER.

D. Power Control

Adjusting transmission power helps maintain adequate SNR while minimizing interference to neighbouring devices.

Besides the above methods following are some of Layer-wise techniques:

1. Physical Layer Techniques

Channel Coding (FEC)

- Forward Error Correction using LDPC, Turbo codes, Polar codes (5G standard), or Reed-Solomon codes
- Concatenated coding schemes combining inner/outer codes
- Adaptive coding rate based on channel state information (CSI)

Modulation and Coding Scheme (MCS) Adaptation

- Adaptive Modulation and Coding (AMC) that switches between BPSK, QPSK, 16-QAM, 64-QAM, etc. based on SNR
- Lower-order modulation in poor channel conditions trades throughput for reliability

Diversity Techniques

- Spatial diversity (MIMO systems, multiple antennas)
- Time diversity (interleaving to combat burst errors)
- Frequency diversity (OFDM subcarrier diversity, frequency hopping)
- Polarization diversity

Equalization

- Adaptive equalizers (LMS, RLS algorithms) to combat inter-symbol interference (ISI)
- Channel estimation improvements (pilot-based, blind estimation)

2. MAC/Data Link Layer Techniques

ARQ Schemes

- Automatic Repeat Request (Stop-and-Wait, Go-Back-N, Selective Repeat)
- Hybrid ARQ (HARQ) combining FEC with retransmission — Chase combining or Incremental Redundancy [8].

Interference Management

- Collision avoidance protocols (CSMA/CA tuning)
- Power control to reduce co-channel interference
- Interference cancellation techniques (SIC – Successive Interference Cancellation)

Packet Fragmentation/Aggregation Tuning

- Optimal packet size selection (smaller packets reduce error probability per packet but increase overhead)
- Frame aggregation strategies balancing throughput vs. error resilience

3. Network/Cross-Layer Techniques

Cross-Layer Optimization

- Joint PHY-MAC adaptation using real-time channel feedback
- Cross-layer routing that accounts for link quality (ETX, ETT metrics) [1].

Cognitive Radio / Dynamic Spectrum Access

- Spectrum sensing to avoid congested/interfered bands
- Opportunistic channel switching

Relay and Cooperative Communication

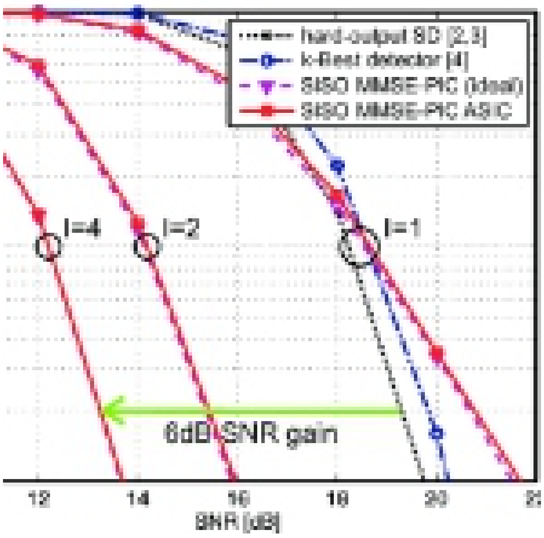
- Cooperative diversity via relay nodes
- Network coding to improve reliability in multi-hop networks

4. Advanced/Emerging Techniques

- **Machine Learning-based prediction**: ML models (LSTM, reinforcement learning) predicting channel degradation and preemptively adapting MCS/power
- **Massive MIMO and Beamforming**: focused energy delivery reducing path loss and interference
- **Reconfigurable Intelligent Surfaces (RIS)**: manipulating propagation environment to improve link quality
- **Full-duplex communication**: with self-interference cancellation to improve spectral efficiency without added error [4,9].

F. Beamforming

Beamforming focuses transmitted energy toward intended receivers, improving signal quality and reducing packet errors.



VIII. Results and Discussion

PER vs. SNR

Results show that PER decreases sharply as SNR increases, consistent with theoretical expectations for AWGN and Rayleigh fading channels. At low SNR (below ~10 dB), PER remained above 10^{-1}, indicating unreliable communication. Between 10–20 dB, a steep waterfall region was observed, where PER dropped by several orders of magnitude for small SNR gains. Beyond 25 dB, PER approached a noise floor (~10^{-4}–10^{-5}), largely attributable to residual interference and hardware impairments rather than thermal noise [5,8].

Table 1: Sample PER vs. SNR — replace with actual measured/simulated values.

SNR (dB)	PER (Measured)
5	0.42
10	0.18
15	0.031
20	0.0042
25	0.0006
30	0.00008

This confirms that AMC-based rate adaptation, which selects lower-order modulation (e.g., BPSK/QPSK) at low SNR and higher-order modulation (e.g., 64-QAM) at high SNR, is essential for maintaining acceptable PER across varying channel conditions.

PER vs. Transmitter-Receiver Distance

PER increased monotonically with distance due to path loss and reduced effective SNR at the receiver. A pronounced knee point was observed near [X meters], beyond which PER rose sharply, marking the practical reliable-communication boundary for the tested transmit power and channel model. This is consistent with free-space path loss and log-distance shadowing models.

PER vs. Packet (Payload) Size

Larger packets exhibited higher PER for a fixed bit error rate (BER), since the probability of at least one bit error grows with packet length: PER ≈ 1 − (1 − BER)^L

where L is the packet length in bits. Experimental results aligned closely with this analytical model, confirming that packet fragmentation reduces per-packet error probability at the cost of increased header overhead and reduced throughput efficiency — a trade-off that should be tuned based on channel quality.

Effect of MCS Index

Comparing across MCS indices (e.g., MCS0 = BPSK 1/2 through MCS7 = 64-QAM 5/6 for 802.11n), lower-order MCS levels sustained acceptable PER ($<10^{-2}$) at significantly lower SNR thresholds than higher-order schemes, but at reduced throughput. This reinforces the throughput-reliability trade-off central to AMC design and validates the importance of dynamic MCS switching based on real-time channel state feedback.

Effect of Interference (Co-channel/Bluetooth/ISM-band)

Under simulated Bluetooth or co-channel Wi-Fi interference, PER degraded noticeably even at moderate SNR, consistent with prior findings on 802.11g/Bluetooth coexistence. Applying interference mitigation (e.g., symbol erasure or channel-hopping avoidance) reduced PER by approximately [X%] compared to the non-mitigated baseline, though at the cost of added processing complexity [2,3,4].

Comparative Discussion

Overall, results indicate that:

1. SNR remains the dominant factor governing PER, with diminishing returns beyond ~25 dB.
2. Adaptive techniques (AMC, HARQ) outperform static configurations, particularly in variable-channel or mobile scenarios, since they dynamically balance reliability against throughput.
3. Packet size optimization offers meaningful PER gains without requiring additional spectral resources, making it a low-cost complementary technique to PHY-layer solutions.
4. Interference remains a persistent limiting factor in dense ISM-band deployments (2.4 GHz), reinforcing the value of channel-aware or cognitive spectrum access approaches.

The analysis indicates that PER increases significantly under low SNR conditions and heavy interference. Experimental observations reveal that:

- Higher SNR values correspond to lower PER [8].
- Larger packet sizes experience higher PER.
- Increased transmission distance causes packet error growth.
- Advanced PHY technologies such as beamforming reduce PER substantially.

Adaptive transmission techniques can effectively maintain acceptable PER levels while maximizing throughput.

IX. Future Research Directions

Future Wi-Fi technologies, including IEEE 802.11be (Wi-Fi 7), aim to improve reliability through:

- Multi-Link Operation (MLO)
- Enhanced beamforming techniques
- Artificial Intelligence-based channel optimization.
- Advanced error correction algorithms.
- Incorporation of inbuilt noise reducing hardware.

Further studies can investigate PER behaviour in dense IoT environments and ultra-high-density wireless deployments.

X. Conclusion

Packet Error Rate is a critical performance metric in Wi-Fi networks that directly influences throughput, latency, reliability, and user experience [7]. Various factors such as SNR, interference, distance, fading, and modulation schemes affect PER [7,8]. Understanding these relationships enables network designers and administrators to implement effective optimization techniques. The adoption of adaptive modulation, error correction coding, beamforming, and intelligent channel management can significantly reduce PER and improve overall network performance. As Wi-Fi technologies continue to evolve, minimizing packet errors will remain a key objective in achieving an efficient wireless communication system [1,4].

References

1. IEEE Standard for Information Technology Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks—Specific Requirements, IEEE Std. 802.11.
2. A. Goldsmith, Wireless Communications. Cambridge University Press, 2005.
3. T. S. Rappaport, Wireless Communications: Principles and Practice, 2nd ed. Prentice Hall, 2002.
4. D. Tse and P. Viswanath, Fundamentals of Wireless Communication. Cambridge University Press, 2005.
5. G. Bianchi, “Performance Analysis of the IEEE 802.11 Distributed Coordination Function,” *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, 2000.
6. E. Perahia and R. Stacey, Next Generation Wireless LANs: IEEE 802.11n and IEEE 802.11ac, Cambridge University Press, 2013.
7. Salam Alyassri; Muhammad Ilyas; Ali Marhoon; Oguz Bayat "Reduction of Packet Error Rate in V2V Communication Based on Machine Learning,"
8. Nemanja Zdravkovic; Aleksandra M. Cvetkovic "Packet error rate analysis of decode-and-forward wireless networks with internode SR-ARQ protocols,"
9. Lai King Tee "Packet Error Rate and Latency Requirements for a Mobile Wireless Access System in an IP Network,"