Journal of Integrated
SCIENCE & TECHNOLOGY

Enhancement of throughput in Bluetooth through adaptive approaches in diverse environment

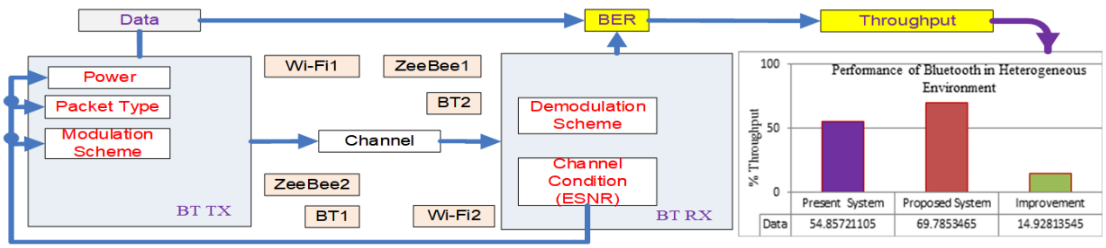
Anil S. Shirsat,[1]* Sandhya. A. Shirsat,[2] Shrishail. B. Mule,[2] S. C. Wagaj,[3]

[1]Electronics and Telecommunications Engineering, PES's Modern College of Engineering, Pune, India, [2]Electronics and Telecommunications Engineering, Sinhgad College of Engineering, Pune India. [3]Rajarshi College of Engineering, Pune, India.

Received on: 23-Mar-2024, Accepted and Published on: 26-Feb-2025

Article

ABSTRACT



Effectively communicating in a crowded ISM band with various Radio Access Technologies is challenging. Coexisting technologies in this band have different data rates and bandwidth, affecting service quality and data transfer capacity. Bluetooth, as an ad-hoc network, needs less bandwidth but is more vulnerable. Assessing channel quality and adjusting transmission schedule can enhance Bluetooth's throughput. Channel quality is determined by analyzing the latest received packet to select modulation technique, power level, and packet type. A MATLAB simulation model in Simulink includes various sources of interference to evaluate Bluetooth performance in a diverse wireless environment. Results show that selecting appropriate modulation techniques and data packets based on channel quality improves performance in the presence of other wireless technologies. Throughput of Bluetooth can increase by 14.92 % by following this approach, nearly reaching the standard maximum data transfer rate. The framework supports different data packets, power levels, and modulation techniques for Bluetooth transmission, offering a simple way to enhance Bluetooth performance in diverse environments.

Keywords: Bluetooth, MATLAB, Throughput, Radio Access Technologies (RAT)

INTRODUCTION

From the last few decades, wireless communication technology has grown at a fast rate, where data rate, coverage area, spectral efficiency, and throughput are significant parameters. Development is not only in licensed band but also unlicensed industrial scientific and medical (ISM) band. In ISM band, various electronics gadgets are operated, such as microwave ovens, cordless telephony, wireless LAN, ZigBee, and Bluetooth.[1] Microwave oven occupies entire 2.4 GHz ISM band, whereas wireless LAN and ZigBee occupies a maximum of 22 MHz and 2 MHz spectrum respectively. Bluetooth is one of important wireless communication candidate widely used for low range, low power, less expensive, and wire replacement technology. Bluetooth, an Adhoc wireless communication network used to transfer the voice and data for short distance.[2] Microwave oven occupies entire 2.4 GHz ISM band, whereas wireless LAN and ZigBee occupies a maximum of 22 MHz and 2 MHz spectrum respectively. Bluetooth, an Adhoc wireless communication network used to transfer the voice and data for short distance. WLAN and ZigBee a high bandwidth communication systems hamper the Bluetooth communication. To alleviate interference caused by these services, Bluetooth uses robust modulation scheme GFSK along with frequency hopping techniques. However, this is not sufficient to combat interference. Various techniques such as adaptive frequency hopping (AFH) technique, frequency band selective technique, and power control techniques are developed. These techniques perform well in crowdy 2.4 GHz ISM band. These techniques utilize spectrum/channel effectively.[3-7] Bluetooth underutilizes channel so Bluetooth has the opportunity to enhance data rate and throughput. Throughput of Bluetooth depends on packet error rate (PER). The number of packets received successfully depends on the modulation technique and channel link condition. By selecting proper packets, throughput can be increased to the average maximum throughput.

*Corresponding Author: Dr. A. S. Shirsat, E&TC Department, PES's Modern College of Engineering, Pune, India.
Tel: +91-9822110071; Email: asshirsat@gmail.com

Cite as: *J. Integr. Sci. Technol., 2025, 13(5), 1107.*
DOI: 10.62110/sciencein.jist.2025.v13.1107

It is essential to adapt higher modulation scheme supporting a high data rate, to increase throughput. It enhances the throughput of Bluetooth at the cost of Eb/No.[8,9]

Since various Radio Access Technologies (RAT) use 2.4 GHz ISM band, it is challenging to maintain maximum throughput of Bluetooth in a heterogeneous scenario. In the heterogeneous environment, it is required to know the channel condition, to achieve maximum throughput[5,6,7]. The main contribution of this paper is to increase the throughput of Bluetooth in the presence of ZigBee, Wi-Fi, other Bluetooth, and hopping interferences. An AFH technique is not sufficient to mitigate these interferences. In this developed technique, AFH is incorporated along with adaptive modulation and Adaptive Power (AP) based on the link quality. Link quality is examined from BER performance of the latest packet received. Three categories are made according to Eb/No and link quality for selection of modulation type, packet type, and power. Firstly at low values of Eb/No and link quality robust BPSK modulation techniques with 10% low power is employed to carry transmission with Data Medium (DM1) and Data High (DH1) packets. Secondly, at medium values of Eb/No, GFSK modulation technique with DM3 and DM5 packets is used at average power.

Finally, at the better link quality and SNR value, DQPSK, a high data rate supporting modulation techniques and packets (DH3 and DH5) are used at 10% higher power. It improves the throughput of Bluetooth to a great extent in a heterogeneous environment. Organization of this paper is as; Section II provides a review of related work. Section III introduces the developed system model. Simulation results and discussion is given in Section IV. In the last section; we conclude the paper along with the future scope.

RELATED WORK

Work reported focuses on various aspects of Bluetooth performance. Major performance parameters considered are security, discovery time, latency, battery lifetime, packet delay, Bit Error Rate (BER), Packet Error Rate (PER), throughput and goodput in the presence of other collocated services. Current internet of things demands high data rate, high throughput performance. To be a good competitor, Bluetooth should have better performance. Throughput performance is calculated from BER. BER, PER, and throughput for various voice synchronus Connection Oriented (SCO) and data Asynchronus Connection Less (ACL) packets are calculated in different scenario [23,24,25,26]. It is clear that throughput is strongly affected in the presence of collocated Radio Access Devices (RADs). Collaborative and non-collaborative techniques are reported to improve the throughput of Bluetooth. In non-collaborative techniques, MAC layer and physical layer work addressed needs modification in present infrastructure. Various modulation schemes are suggested to increase data rate and throughput at the cost of higher SNR[6,14]. Few techniques employ Kalman Filtering (KF) and derivatives of KF, such as interactive KF, linear KF, extended KF, and unscented KF along with GFSK demodulation to improve Bluetooth performance[15,16].

Adaptive frequency hopping techniques are employed by selecting right frequency channels for communication in Bluetooth transceiver. Adaptive packet selection scheme is also suggested to improve the throughput performance of Bluetooth in the presence of RADs. These techniques rely on Forward Error Correction (FEC) or radio link analysis. The outcome of FEC is used to select the packet type, in a heterogeneous environment[5,6,7]. In radio link analysis, link quality is calculated based on BER of the recent packet received. Packet selection is made based on link quality assessment. However, at low SNR values throughput performance has scope for improvement. For performance analysis of the Bluetooth, ACL packets are commonly used in the presence of Wi-Fi only. Error detection and correction convolution codes are applied along with hamming code to correct the error bits in payload at receiver. Some improvement is observed in the performance of Bluetooth[9,17]. Improvement in Bluetooth performance is equally vital in the presence of 802.11g and other devices in automotive domain.[18,19.20]

In collaborative strategy services such as Bluetooth, ZigBee, and Wi-Fi have to allocate fix frequency band for operation, which is impossible in the present scenario. The channels which are not utilized by wi-Fi should be used by other RADs. This restricts hopping sequence of Bluetooth. In a collaborative method, various mechanisms are reported such as packet fragmentation, adaptive packet strategy based on channel behavior. This improves the throughput performance in either network closer to the baseline performance.[21-22]

From the literature survey, it can be concluded that the performance of Bluetooth in terms of BER, PER, and throughput can be enhanced at certain level in the presence of other RADs with hardware modification in Bluetooth. This will increase overheads on Bluetooth module. To be a right candidate in the internet of things, Bluetooth should have adequate interference rejection capabilities, high data rate, and maintain baseline performance for throughput, goodput with adaptive modulation, power scheme in a heterogeneous wireless environment.

METHODOLOGY

Figure 01 shows the developed block diagram of the system simulated in MATLAB Simulink. Data transmission is carried through Asynchronous Connectionless (ACL) packets DMk and DHk.

1. Packet types, structure, and format: Types of packets used in Bluetooth are control packets, synchronous packets, and asynchronous packets. Control packets hold radio links related information such as hop frequency, clock, connection request, connection establishment, and security. Synchronous connection orientation consists of voice information. SCO link has voice and data packets DV, HV1, HV2, HV3, and synchronous connection-oriented with repeated transmission (SCORT) voice packets[10]. ACL packets carry the data information. ACL has DMk and DHk (where k=1, 3 and 5) packets. General Bluetooth packet format consists of Access code of 68 to 72 bits, header information 54 bits and 0 to 2745 bits for data payload along with CRC trial bits. Some packets employed 1/3 and 2/3 rate repetition codes.[2,11]

2. Modulation and Packet Selection: Three different modulation schemes are used based on channel quality. For low link quality up to 8 dB, the BPSK modulation scheme is used to transmit data through DM1 and DH1 packets. In medium link quality between

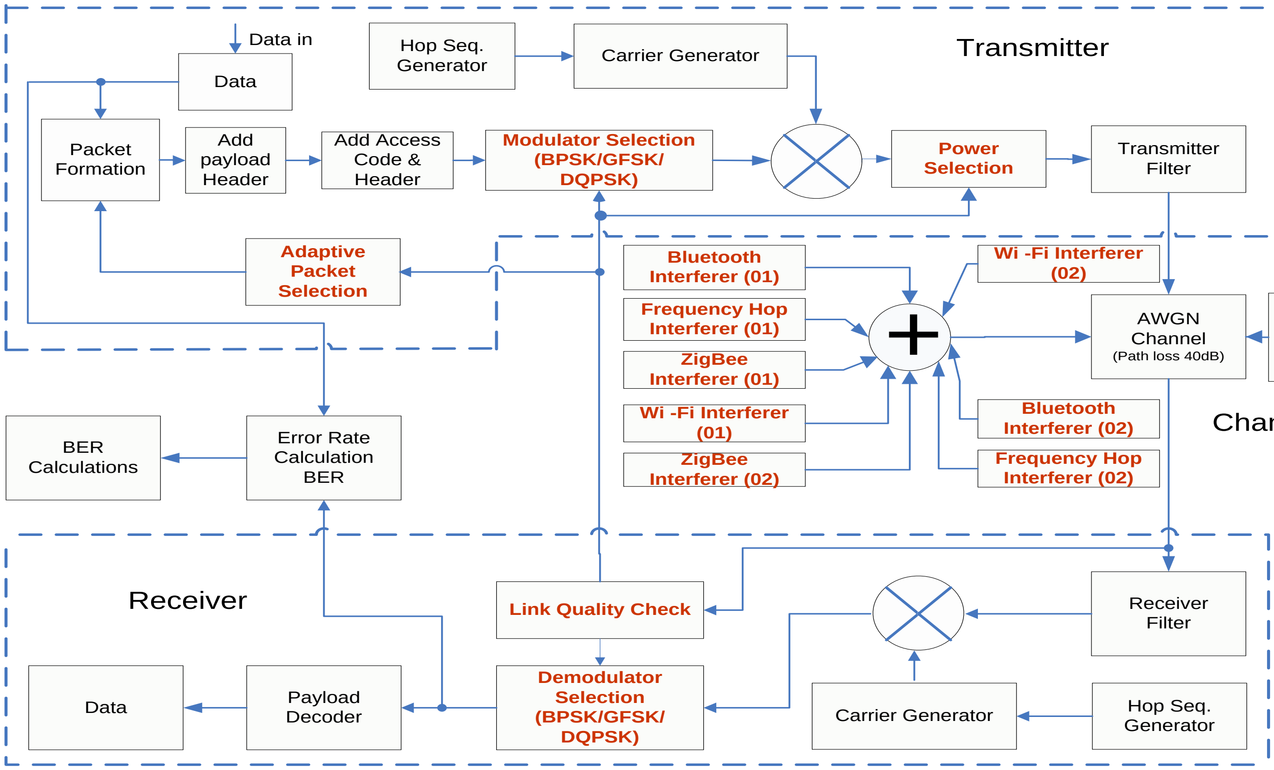


Figure 1 Block Diagram of Bluetooth Transceiver System

8 to 9.9 dB GFSK modulation schemes is employed with moderate power to transmit the data through DM3 and DM5 packets. For good link quality, a higher-level DQPSK modulation is scheme used with more transmission power. It transmits the data at a fast rate with high data rate packets such as DH3 and DH5. Figure 02 gives the details of modulation selection in different link quality scenario. Bluetooth uses GFSK (Gaussian Frequency Shift Keying) modulation technique. For 1 MHz bandwidth, data rate supported is 1 Mbps at 0.3 to 0.32 modulation index and 0.5 bandwidth bit period product. GFSK modulation scheme is termed as Continuous Phase FSK. High-frequency components in the modulated signal are reduced due to continuous phase variation in GFSK signal. This signal is made smoother, instantaneous frequency stabilized by employing filter. The Gaussian frequency pulse shaper is used for the reduction of sidelobe obtained in phase continuity.

The impulse response of Gaussian filters is given by the Eq. 01. GFSK signal is expressed in eq. 02 [15,24].

$$\boldsymbol{h(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} H(\omega)\, e^{i\omega t} d\omega \;\; = e^{-\frac{1}{2}\left(\frac{t}{\tau}\right)^2}} \qquad (01)$$

Where H(ω) = √(2π) 〖 τ e〗^(- 1/2 〖(τω)〗^2) at τ - Constant

$$\boldsymbol{S_{GFSK}(t) \;\; Re\left[\left(\sqrt{\frac{2E_b}{T_b}}\; e^{j2\pi\, mi\, \Delta f t}\right) e^{j2\pi f_c t}\right]} \qquad (02)$$

$$S_{GFSK}(t) = \sqrt{\frac{2E_b}{T_b}}\; \cos(\,2\pi f_c\, t + \,2\pi\, mi\, \Delta f\, t) \qquad (03)$$

Where mi = modulation index, Tb = bit period, 1≤ mi and 0 ≤ t ≤ T_b ,. Carrier is shifted by $mi\, \Delta f$.

Let $d(t) = \sum_{n=0}^{n} I_n\, g(\tau - nT_b)$ be the signal, g(t) be the rectangular pulse with amplitude I_n. Complex transmitted baseband signal will be

$$\boldsymbol{S_{TR}(t) = \; Re\left[\, A\;\; e^{j\,\varphi_m(t)}\right]} \qquad (04)$$

$$\varphi_m(t) = \pi\, mi \sum_{-\infty} [\, I_n\; g(\tau - nT_b)\, d\tau] \;\; \varphi_0 \qquad (05)$$

Where

I_(n) - Mapped to ± 1 as per binary input data, A - amplitude of a transmitted signal, φ_m (t) -integrated phase

φ_0- The initial phase of the carrier signal, φ_0=0 to avoid the loss of generality.[27,28]

3. Filtering and Radio Channel: For the GFSK modulation scheme, the modulated signal passed through a Gaussian filter with 24-tap. Product of bandwidth of filter and symbol duration period is 0.5 with 28 % modulation index. For BPSK and DQPSK signal is applied to root-raised cosine (RRC) filter at roll-off factor 0.35.[15,25]

4. Performance Parameters and Calculation: Bit Error Rate (BER) states the total number of bits in errors, Packet Error Rate (PER) refers to the number of packets in error and Throughput refers a number of bits received successfully per second at receiver. BER, PER, and throughput are significant parameters emphatically exaggerated in a noisy background when Bluetooth devices operated in a heterogeneous environment. BER, PER, and Throughput of Bluetooth degrade with increasing numbers RADs. Bluetooth performance in terms of BER and throughput is

calculated in the presence of RADs. Monte Carlo based MATLAB Simulink simulation is carried out to calculate BER performance using bertool. Performance parameters are calculated from BER. The PER and throughput (***Th***) is calculated using the following relationships at different values of Eb/No [1,26].

$$\boldsymbol{Th} = (\boldsymbol{I} - \boldsymbol{PER}) * \boldsymbol{M} * \boldsymbol{Rmax} \tag{06}$$

$$PER = (1 - (1 - BER)^{PL}) \tag{07}$$

Where

M -Represents the number of bits/symbol (1 for GFSK and BPSK, 2 for DQPSK), Rmax - maximum supported data rate for a particular packet.

5. Link Quality Check: The quality of the link is essential to decide the modulation scheme, power, and packet type. By transmitting a few DM1 packets with BPSK modulation technique at 1mw power, channel quality is checked. Steps used for testing the link quality are

- A signal is taken from the input of Bluetooth receiver.
- Link SNR (ESNR) is calculated from available spectrum at the receiver.
- The absolute value of maximum ESNR is taken.
- This value is compare with a threshold. Thresholds are set by taking readings number of times at different values of ESNR at different interference scenario.
- The calculated value is used to select modulation scheme, packet type, and power by comparing the values with other thresholds.

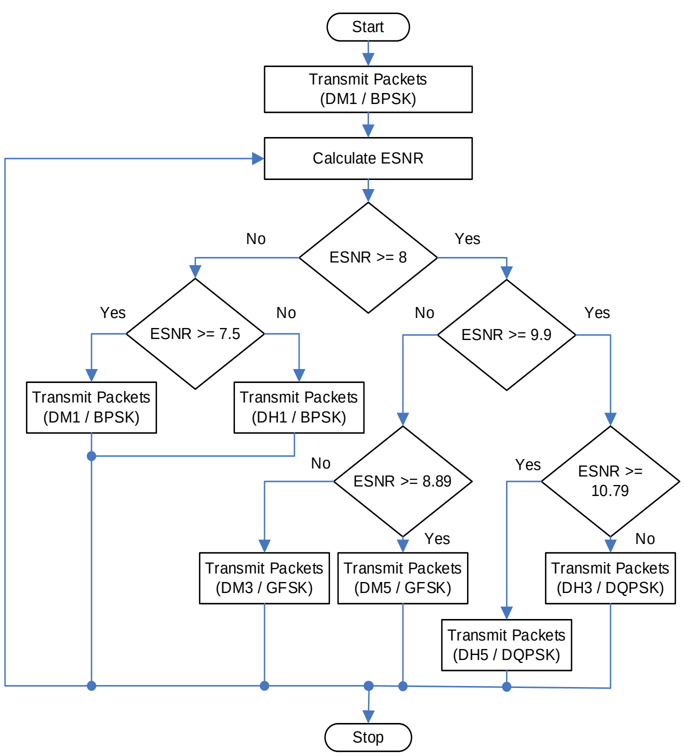


Figure 2. Flow Diagram for Selection of Bluetooth Parameters

6. Adaptive Packet Selection: Link quality is examined on the last packet received. From this link, quality ESNR value is obtained, to decide threshold values. Thresholds are set to select packet type, modulation technique, and transmission power.

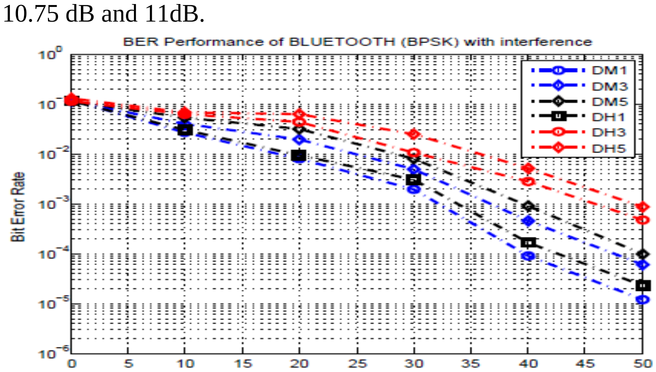
Low data rate packets DMX are transmitted with BPSK robust modulation technique, while DM3 and DM5 are transmitted with the help of the GFSK modulation scheme. High data rate supporting the DQPSK modulation scheme is employed to transmit higher data packet DH3 and DH5. Transmitted power is selected according to the modulation technique used. For BPSK, 10 % power is reduced, while 10 % of power increased in the DQPSK modulation scheme. GFSK maintains the same transmission power.

7. Interference Generator: Bluetooth transceiver experiences interference from RADs such as Wi-Fi, ZigBee, Hopping interference, cordless telephony, RFID tags, Microwave oven, and other Bluetooth networks which are close vicinity. Few of these are simulated in MATLAB Simulink model. Performance of Bluetooth is evaluated in the presence of these RADs over AWGN channel. The performance of Bluetooth gets hampered by increasing RADs. An attempt is made to create a heterogeneous environment by employing Wi-Fi-, ZigBee, hopping interference, and other Bluetooth transciever two in numbers.

RESULTS

In this simulation Bluetooth modulation technique, adaptive power, and adaptive packet selection strategy are integrated. Monte Carlo based MATLAB Simulink is carried out multiple number of times to analyze the performance of Bluetooth in the presence of RADs. BER performance of Bluetooth shown in Figure 3 is obtained from this simulation for BPSK, GFSK, and DQPSK modulation techniques with and Figure 4 without RADs. From the graph, it is clear that the desired BER performance of Bluetooth can be achieved by employing AFH and AP at the cost of high Eb/No. Throughput performance is shown in Figure 5 is increased but less than the average maximum value. To increase the throughput value packet and modulation scheme should be selected based on available link quality.

Performance of the developed system in heterogeneous environments is presented in Figure 6. With the estimation of link quality, at ESNR value 8.25 dB and 8.8 dB BPSK modulation with DM1 and DH1 packets respectively outperforms desired BER in a noisier environment. In less noisy link GFSK modulation scheme with DM3 and DM5 packets gives excellent performance at 9.2 dB and 10 dB ESNR values. While high data rate DQPSK modulation technique provides desired performance for DH3 and DH5 packets at 10.75 dB and 11dB.



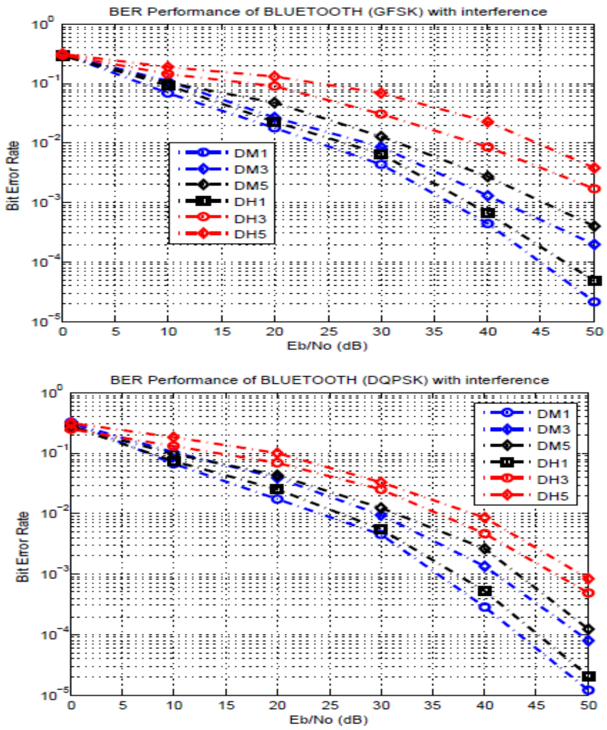


Figure 3 BER Performance of Different Modulation Schemes with and Without Noise.

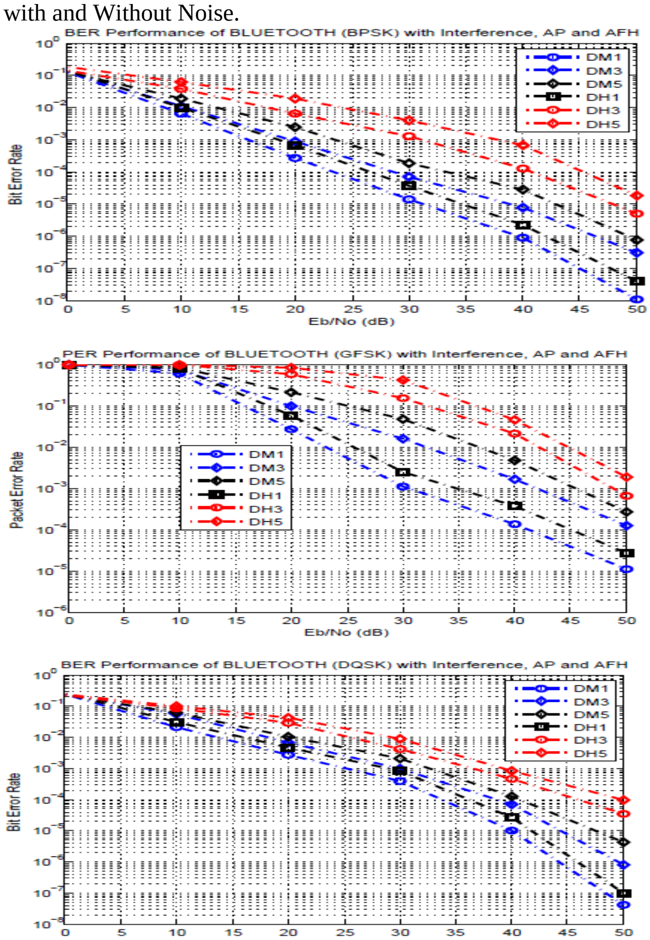


Figure 4 BER Performance of Different Modulation Schemes with and Without Noise.

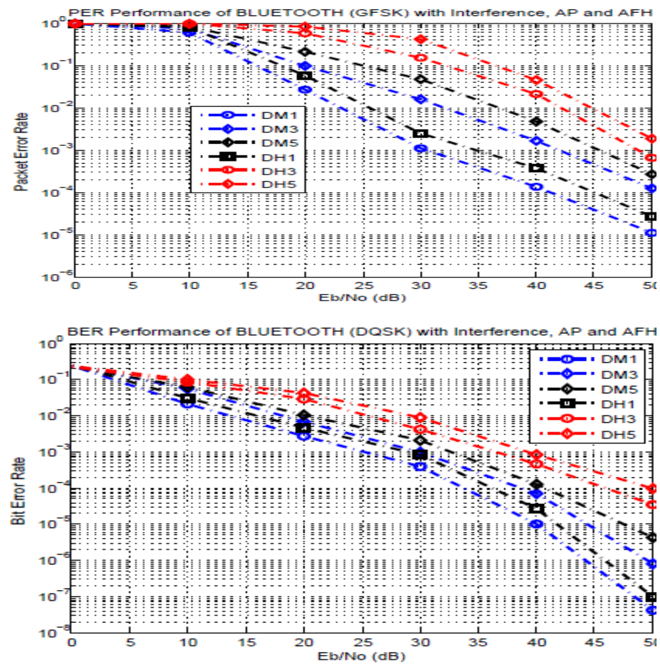


Figure 5 Performance of the Developed System in Heterogeneous Environments.

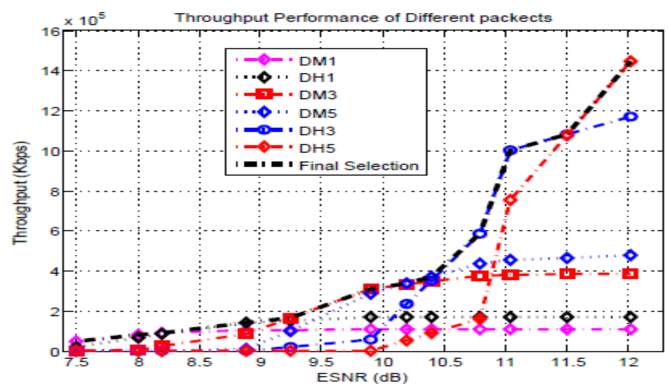


Figure 6 Performance of the Developed system in Heterogeneous Environments.

This enhances the throughput performance of Bluetooth close to maximum throughput value. Average maximum throughput of Bluetooth with the conventional method is 54.86 %, which shows that throughput performance is required to enhance. By employing packet, power, and modulation technique selection, the throughput is closed 69.79 %, which is enhanced by 14.928 %.

CONCLUSION

In this paper, a throughput improvement technique has been devised for Bluetooth within a diverse wireless environment. The methodology revolves around evaluating link quality based on the reception of the most recent packet. The outcomes of the Bluetooth simulations lead to the deduction that through the acurate selection of packet, modulation scheme, and power in alignment with the available link quality, the throughput can be boosted to the average maximum throughput level. This adaptive selection approach contributes to a 14.92 % increase in throughput. The study puts forth certain recommendations to upgrade the Bluetooth performance regarding Bit Error Rate (BER) and Throughput for forthcoming Bluetooth research endeavors.

CONFLICT OF INTEREST

The authors declare that there is no academic or financial conflict of intetest for this work.

REFERENCES AND NOTES

1. A. K. Arumugam, S. M. D. Armour, B. S. Lee, M. F. Tariq, A. R. Nix Consumer electronics application and coverage constraints using Bluetooth and proposed Bluetooth evolution technologies. *IEEE Trans.* on *Consumer Electronics* **2001**, 47(3), 283–293.
2. JN-AN-1079 Coexistence of IEEE 802.15.4. in the 2.4 GHz Band-1v0.pdf. **2008**, 1–34.
3. A. Zanella, A mathematical framework for the performance analysis of Bluetooth with enhanced data rate. *IEEE Trans. on Communications*, **2009** 57(8), 2463-2473.
4. V. Kulkarni, K. Narayana, S. K. Sahoo. A Survey on Interference Avoiding Methods for Wireless Sensor Networks Working in the 2.4 GHz Frequency Band. *Journal of Engineering Science and Tech. Review*, **2020**, 13(3).
5. F. Guo, Q. Xiao, Q. Xiao. Bluetooth channel quality simulation, estimation and adaptive packet selection strategy. *WSEAS Trans. Information Science and Applications.* **2009**, 6(1), 84–94.
6. L. Jing, C.Wanzhong, Z. Xiaohui. Achievement of Bluetooth adaptive packet selection strategies based on SNR estimation. *J. China Universities of Posts and Telecommun.* **2016**, 23(1), 8–13.
7. C. H. Shih, K. Wang, H. C. Shih. An adaptive Bluetooth packet selection and scheduling scheme in interference environments. *Computer Communications.* **2006**, 29(11), 2084–2095.
8. R. Challoo, A. Oladeinde, N. Yilmazer, S. Ozcelik, L. Challoo. An overview and assessment of wireless technologies and coexistence of ZigBee, Bluetooth and Wi-Fi devices. *Procedia Computer Science, Elesevier.* **2012**, 12, 386–391.
9. M. A. M. El-Bendary, A. Haggag, A. Optimum Piezo-Electric Based Energy Harvesting for Low-Power Wireless Networks with Power Complexity Considerations. *Wireless Pers. Commun*. **2023,** 2355–2377.
10. S. A. Shirsat, A. S. Shirsat, V. G. Raut, R. P. Patil. An adaptive pilot density based data rate enhancement of mobile WiMAX. Journal of Integrated Science and Technology **2025,** 13(3), 1058, 1-5.
11. F. Qamar, M. H. D. N. Hindia, K. Dimyati, et al. Interference management issues for the future 5G network: a review. *Telecommun. Syst*. **2019,** 71, 627–643.
12. A. S. Shirsat, S. A. Shirsat, D. Y. Yadav. Performance of Bluetooth in Homogeneous Environment. *International Journal of Engineering and Technology*. **2018**, 7(4.36), 506-510.
13. A. S. Shirsat, S. A. Shirsat, S. C. Wagaj, R. Sahu, M. A. Kango. Bluetooth: A Smart Solution to the Internet of Things for Smart Home *The Indian Journal of Technical Education,* **2024**, 47 (2), 302-311.
14. Sharad S. Wagh, Avinash More, Prashant R. Kharote, Performance Evaluation of IEEE 802.15.4 Protocol Under Coexistence of WiFi 802.11b, Procedia Computer Science, Elsevier, **2015**, 57, 745-751.
15. A. S. Alghamdi, M. N. Ali, M. A. Zohdy. Robust Non-Coherent Demodulation Scheme for Bluetooth Voice Transmission Using Linear, Extended, and Unscented Kalman Filtering. *Journal of Signal and Information Proc*. **2015**, 06(01), 9–27.
16. M. A. M. El-Bendary, et. al. Throughput Study of Low-Rate Communications. In: Developing Security Tools of WSN and WBAN Networks Applications. *Lecture Notes in Electrical Engineering*, *Springer*, *Tokyo*, **2015.** 316.
17. J. H. Kleinschmidt, W. C. Borelli, M. E. Pellenz. An energy efficiency model for adaptive and custom error control schemes in Bluetooth sensor networks. *AEU- International J. of Electronics and Commun.* **2009**, 63(3), 188–199.
18. A. Mourad, S. Muhammad, M. O. Al Kalaa, P. A. Hoeher, H. Refai. Bluetooth and IEEE 802.11n system coexistence in the automotive domain. *IEEE Wireless Commun. and Netw.* **2017,** 1-6.
19. L. Polak, J. Milos, Performance analysis of LoRa in the 2.4 GHz ISM band: coexistence issues with Wi-Fi. *Telecommun. Syst*. **2020**, 74, 299–309.
20. A. C. C. Hsu, D. S. L. Wei, C. C. Jay Kuo, C. J. Chang Coexistence Wi-Fi MAC Design for Mitigating Interference Caused by Collocated Bluetooth. *IEEE Trans. Computers*. **2015**, 64(2), 342–352.
21. Kondo T., Fujita H. Yoshida M., Saito T. Technology for Wi-Fi Bluetooth and WiMAX coexistence. *Fujitsu Scientific and Technical Journal*, **2010.** 46(1), 72–78.
22. R. Mubashar, M. A. B Siddique, A. U. Rehman. Comparative performance analysis of short-range wireless protocols for wireless personal area network. *Iran J. Comput. Sci.* **2021**, 4, 201–210.
23. J. R. Luque, M. J. E. Morón, Casilari A characterization of the performance of Bluetooth 2.x + EDR technology in noisy environments. Wireless Netw. **2015**, 21(6), 1969–1984.
24. Bulić P, Kojek G, Biasizzo A. Data Transmission Efficiency in Bluetooth Low Energy Versions. *Sensors*. **2019**; 19(17), 1-17.
25. Xu, H., Yan, Z., Li, B., & Yang, M.. Modeling and analysis of the performance for Bluetooth low energy. *IEEE Communications Letters*, **2024**, 28(3), 732-736.
26. A. S. Shirsat, S. A. Shirsat, D. M. Yadav. Performance Evaluation of Pulse Shapers In Bluetooth. *International J. f Innovative Technology and Exploring Engineering.* **2019**, 8(5), 1227–1233.
27. Y. Yao, H. Tang, Z. Zeng. Efficient Bluetooth Video Transmission with Resource Manager. *Int. Journ. of Signal Proc. Image Proces., and Pattern Recog.* **2016**, 9(2), 405–414.
28. V. K. Munir, D. O. Olsen, Design of an Integrated GFSK Demodulator for a Bluetooth Receiver. *Informatics and Mathematical Modeling, Technical University of Denmark, Lyngby, Denmark.* **2001,** 25-33.