Improved counterplan for interference in same-band information transmission and reception

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ABSTRACT

Wireless communication technologies operating in the 2.4 GHz band, such as Wi-Fi, Bluetooth, ZigBee, and others, often face challenges related to mutual interference. These technologies share the same unlicensed frequency spectrum, which can lead to various types of interference, affecting performance, reliability, and data throughput. This paper addresses the issue of mutual interference in communications occurring within frequency bands commonly used in daily life. Through this, it conducts an in-depth study on information processing between wireless devices and the control of communication components. Specifically, it examines interference phenomena in the widely used 2.4 GHz band by analyzing communication methods where such interference is likely to occur. By investigating the characteristics of Wi-Fi, Bluetooth, and ZigBee, this study analyzes interference phenomena and proposes an algorithm to mitigate them. To mitigate this, this paper proposes a multi-layered method integrating adaptive filtering, dynamic frequency allocation, advanced error correction, and intelligent scheduling mechanisms.

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1. INTRODUCTION

With the advancement of information and communication technology, various smart wireless devices are increasingly being used in daily life. These devices exchange data through mutual wireless communication in different ways [1]. However, as the number of wireless devices continues to grow, the frequency bands available for wireless communication remain limited, making interference between devices using the same frequency band inevitable. Such interference, including signal congestion, can sometimes lead to serious issues. Eliminating these interference phenomena is essential for improving the stability of wireless communication and advancing wireless communication technology [2]. This study explores algorithms for the efficient use of frequency bands in response to the growing demand for wireless communication. It delves into detailed wireless communication mechanisms, identifies potential issues in existing technologies, and investigates improvements. To ensure the stability of wireless communication and enhance the efficiency of data transmission and reception, various information processing algorithms have been studied. Therefore, this research analyzes widely used wireless communication technologies operating in common frequency bands and develops an algorithm to mitigate interference between them. This paper focuses on mutual interference that may occur in commonly used frequency bands in everyday life. It examines traffic management techniques employed in wireless communication technologies within these bands and proposes an algorithm to reduce interference in data transmission and reception through wireless communication.

2. BLUETOOTH

Bluetooth is a communication standard for wireless communication that operates in the industrial, scientific, and medical (ISM) frequency band and is provided free of charge concerning the intellectual property rights of related technologies [1]-[3]. This communication standard exhibits noticeable mutual interference when transmitting and receiving information with other communication systems. However, when only systems using the same standard are employed, the interference is significantly reduced [4]-[6]. As a result, establishing a network in the 2.4 GHz band leads to increased frequency interference due to the rising number of systems operating within this band and their growing occupancy. Consequently, the required margin for the established network must accommodate the increased interference in the frequency band [7]-[9]. Bluetooth transmits data using radio channels at a data transmission rate of 1 Mbps for both voice and data packets and functions as a PAN with an operating range of up to 10 meters. The transmission power (Tx) is limited to 100 mW (+20 dBm) or lower, which is relatively lower than other wireless communication methods [10]-[12]. It uses frequency-hopping spread spectrum (FHSS) technology, a communication method that shifts the carrier frequency at predetermined intervals to reduce interference caused by the operation of other communication devices in the frequency band used by the device [13]-[15]. Interference between communication devices using only Bluetooth is either recoverable or can be avoided through coexistence technologies. Figure 1 illustrates the time slot allocation in Bluetooth communication.

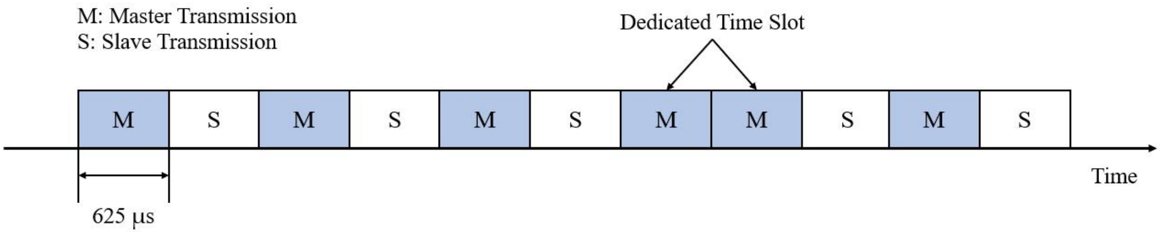

Figure 1. Time slot assignment of Bluetooth

Synchronous connection-oriented (SCO) is one of the two types of links used in Bluetooth, and it is through this link that voice transmission occurs in Bluetooth [16]-[18]. In Figure 2, T1, T2, and T3 show the transmission slots for the master link in the SCO link, while Slot R1, R2, and R3 represent the return path from the slave to the master. The SCO link is a point where voice packets are transmitted or received in reserved time slots at regular intervals, exhibiting symmetric characteristics. SCO packets transmit data every sixth slot at intervals of 3.75 ms [19]-[21]. Additionally, data is transmitted from the master to the slave, and in the next slot, it is returned from the slave to the master. This creates a point-to-point connection between the master and slave, and once the SCO data packet is transmitted, it is not retransmitted [22]-[24]. As a result, the SCO link places significant importance on temporal factors and is therefore suitable for data transmission that does not rely heavily on reliability. Hence, it is an ideal link for voice transmission [25]-[27].

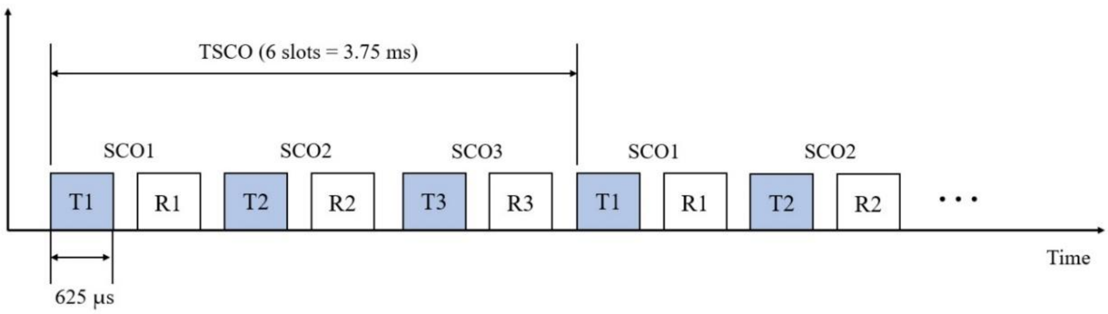

Figure 2. SCO voice slot of Bluetooth

Bluetooth data transmission uses the asynchronous connection less (ACL) link, which differs from the SCO link typically used for voice transmission [28]-[30]. When data is transmitted, errors in the transmitted data are critical, so if an error occurs, the affected packet must be retransmitted. ACL link transmission involves the device receiving the signal and processing the information, called the receiver, which repeatedly sends packets until it receives an acknowledgment signal. The receiver checks the received packet's information and uses cyclic redundancy check (CRC) to determine if the packet was received correctly. The throughput (bps) in ACL-Tx is monitored, and the bit error ratio (BER) has a low dependency. The receiver specifies an automatic repeat request number (ARQN) in the packet's header and sends it back to the sender via the return path. The sender checks the ARQN value to determine whether the transmission was successful. In one-way communication from the master to the slave, the slave sends a dummy packet in the next slot (with no payload in the NULL or dummy packet). Figure 3 shows the packet sent in the first slot of the ACL link data-medium rate (DM1), followed by the slave sending a NULL packet with an acknowledgment code (ACK) in response. The master will transmit again in the next slot.

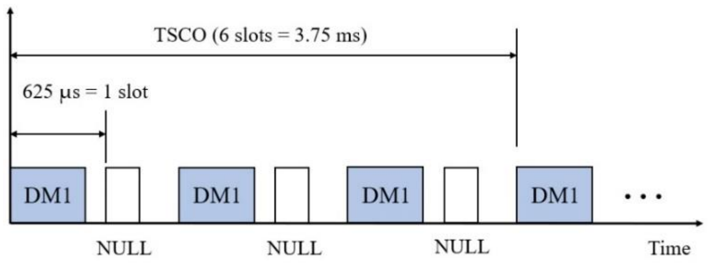

Figure 3. ACL data slot assignment of Bluetooth

3. ZIGBEE

ZigBee is a communication standard for wireless communication that forms a personal area network (PAN) through low-power digital radio. The ZigBee technology standard is based on the IEEE 802.15 standard, and in 2003, the IEEE 802.15 Work Group adopted ZigBee as the low rate wireless personal area network (WPAN) standard [31]-[33]. The Low Rate WPANs (IEEE 802.15.4/LR-WPAN) were established with a focus on ISM applications, offering low power and low cost, which were not previously considered in WLANs. The IEEE 802.15.4 standard defines the Physical and media access control (MAC) layers with low transmission speeds in the 2.4 GHz ISM band [34]-[36]. This standard defines 16 channels with a 2-3 MHz band gap between them. The transmitted bytes are split into two 4-bit symbols, each assigned to one of 16 pseudo-random values. These data symbols are mapped to one of the 32-chip sequences using the Offset-QPSK (O-QPSK) modulation, resulting in a transmission speed of 250 kbps [37]-[39]. Figure 4 shows the ZigBee protocol stack, highlighting the parts defined by the IEEE 802.15.4 standard and the application layer defined by the ZigBee Alliance [39].

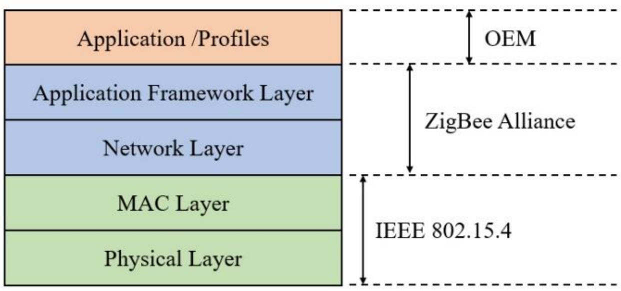

Figure 4. Protocol stack on ZigBee

Figure 5 illustrates the packet structure of IEEE 802.15.4, comprising the synchronization header (SHR) and the physical header (PHY Header, PHR). The SHR header consists of a 4-byte Preamble and a 1-byte start of frame delimiter (SFD), which is set to 0x7A to indicate the start of the frame [40]. The PHR is 1 byte long and contains a field that describes the byte value for the payload [40]-[42]. In this packet structure, the maximum size of the packet, including the header, can reach 133 bytes.

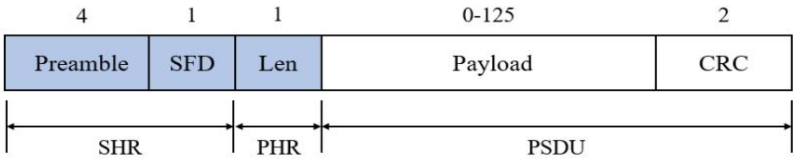

Figure 5. Packet structure for IEEE 802.15.4

4. WI-FI

Wi-Fi is a short-range data transfer protocol for devices based on the IEEE 802.11 wireless communication standard. It is a high-performance wireless LAN technology, and most of the standards derived from IEEE 802.11 (such as 802.11n, 802.11ax, 802.11be) operate in the ISM band, specifically the 2.4 GHz range, similar to Bluetooth and ZigBee [43]-[45]. The transmission power (Tx) of IEEE 802.11 is approximately 10-100 times larger than that of IEEE 802.15.1 and IEEE 802.15.4. In the ISM band, the unlicensed 2.4 GHz range uses two modulation methods for wireless communication: FHSS and direct sequence spread spectrum (DSSS). While Bluetooth primarily uses FHSS, Wi-Fi and ZigBee use DSSS as their modulation method. Wi-Fi is primarily used to connect electronic devices to a local area network (LAN). Wi-Fi employs DSSS for modulation, and each channel has a bandwidth of 22 MHz. Within the permitted frequency range, three non-overlapping channels can be used concurrently [46]-[48]. The IEEE 802.11 standard uses Barker codes, which have good autocorrelation characteristics, and uses 11-bit pseudo-random noise (PN) codes to encode information bits at speeds of 1 and 2 Mbit/s. To increase the data rate, IEEE 802.11 uses complementary code keying (CCK), which encodes 6 information bits into 8 chip symbols.

Figure 6 shows the key functions of the MAC protocol in IEEE 802.11. The IEEE 802.11 standard uses CSMA/CA, including ACK, and employs request to send (RTS) and clear to send (CTS) packets [9]. This protocol specifies the minimum time required to respond with an acknowledgment when receiving a frame (Short Inter-Frame Space, SIFS) and the minimum delay when trying to transmit data after the previous transmission distributed inter-frame space (DIFS). The contention window (CW) is divided into slots, as shown in Figure 2-7. A node selects a slot and waits for a connection to the medium using a uniform random distribution before making a transmission. The node selects the fastest slot to begin contention for the window. If the maximum size of the contention window (1,023 slots) is satisfied, the values of the 31 slots in the contention window are initialized. If a failure to connect to the medium occurs, the values of 62 slots are initialized.

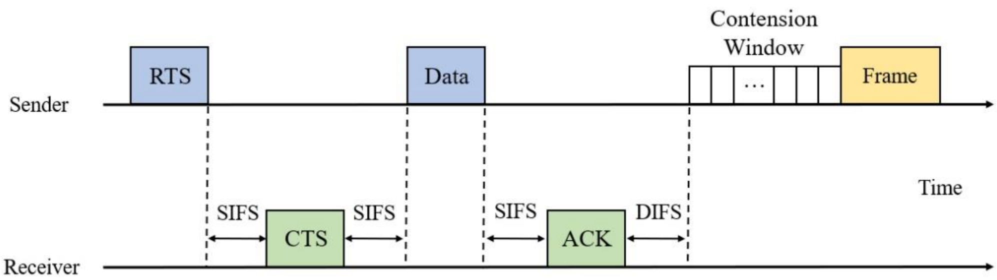

Figure 6. Configuration of MAC protocols in IEEE 802.11

5. INTERFERENCE BETWEEN WIRELESS COMMUNICATION IN 2.4 GHZ BAND

In IEEE 802.15 TG2, coexistence mechanisms between communication standards used in wireless communication are proposed. The proposed coexistence mechanisms in this TG include cooperative and non-cooperative approaches. The cooperative mechanisms include the enhanced time algorithm (META) and the adaptive wireless media access (AWMA) [49], [50]. The META mechanism positions Bluetooth nodes and 802.11 stations on the same physical device, enabling communication between them. This mechanism uses a centralized controller to monitor the traffic of Bluetooth and 802.11, allowing data exchange between wireless systems that share the same physical device. It provides authentication for all transmitted packets and gathers information about the activity of Bluetooth and 802.11, predicting potential collisions that might occur during coexistence. When Bluetooth's SCO traffic has a higher priority than other 802.11 data packets, 802.11 response packets operate with higher priority than Bluetooth packets. The AWMA mechanism functions at the MAC layer and is based on the principles of time division multiple access (TDMA). This mechanism assumes that Bluetooth's master node and the 802.11 access point are located on the same physical device, allowing alternating transmissions. In this way, Bluetooth and 802.11 devices avoid timing overlaps. The 802.11 access point transmits beacons at regular intervals, and the interval between beacons is divided into sub-intervals for each Bluetooth and 802.11 traffic. However, the AWMA mechanism does not apply when the SCO link is in use [18], [20]. Both the META and AWMA mechanisms have the limitation that they cannot mitigate interference unless other wireless devices are adjacent. For these mechanisms to be effective, the 802.11 receiver must be aware of the hopping pattern of Bluetooth's frequency at the same timing, meaning the two devices must be on the same physical device. Non-cooperative coexistence mechanisms use adaptive frequency hopping (AFH) technology, which includes adaptive packet selection and scheduling, Tx control, and rate adjustment techniques. AFH technology reduces the probability of frequency overlap between Bluetooth and 802.11 signals, categorizing Bluetooth's hopping channels into Good, Noise, and Interference states. The federal communications commission (FCC) defines two modes (Mode-L, Mode-H) [17]. Mode-L removes channels recognized as interference from the hopping sequence, while Mode-H separates Bad channels (recognized as interference) and Good channels, grouping them together to reduce the use of Bad channels and increase the use of Good channels in the hopping sequence. Using adaptive packet selection and scheduling techniques is an excellent choice for mitigating interference between 802.11 and Bluetooth. By selecting the appropriate Bluetooth packets based on the frequency hopping state, Bluetooth data throughput increases. Additionally, by selecting hops that avoid the 802.11 band, interference between wireless systems can be alleviated.

To analyze the mutual interference between Wi-Fi and Bluetooth communication standards, the following conditions are assumed: the Bluetooth device has enough power to cause interference with the Wi-Fi device. The two wireless communication devices transmit data at the same time on the same frequency, and any collisions that occur during data transmission are received with a unified error probability. In IEEE 802.11 Wi-Fi, the DSSS method is adopted with a bandwidth of 22 MHz. In IEEE 802.15.1 (Bluetooth), an SCO link is used for voice transmission, and asynchronous connection-less (ACL) links are used for data transmission. By considering retransmissions and SCO links, the impact of interference on voice links is reduced.

6. COUNTERMEASURES AND RESULTS

To evaluate the effectiveness of the proposed counterplan for mitigating interference in same-band information transmission and reception, several performance metrics are considered. These metrics assess signal quality, network efficiency, and overall system robustness. IEEE 802.11 operates at a transmission speed of 11 Mbps and has an interaction range of 100 meters. In this study, a system utilizing DSSS is adopted. The network configuration consists of a basic service set (BSS), which includes multiple wireless stations that share the same spreading sequence and use MAC functionality. These wireless stations communicate either by directly forming an Ad-hoc network or through a central access point that assigns connections to a wired network [35]. The IEEE 802.11 standard defines two main MAC functions: the distributed coordination function (DCF) and the point coordination function (PCF). DCF allows for asynchronous data transmission based on the CSMA/CA protocol. PCF, based on polling from the access point, supports real-time traffic but lacks specific service features based on traffic characteristics. Therefore, it is not commonly implemented in commercial devices, and this study considers using DCF. Bluetooth supports communication between devices located within 10 meters of each other. Additionally, when devices in the network communicate without pre-defined configurations, each device assumes the role of master or slave, forming a network based on their own coordination protocol. Bluetooth networks are composed of a master device and slave devices that communicate with it, forming a Piconet [4]. Figure 7 explains the channel used in Bluetooth for frequency hopping/time-division duplex (FH/TDD). Bluetooth adopts FH/TDD, where the channel is divided into slots of length T. Each slot uses a different hopping frequency, and the hopping rate is 1600 hops per second. A packet is transmitted in intervals/slots, with subsequent slots using TDD mode, alternating between transmission and reception. The channel uses multiple hops with a 1 MHz frequency gap, and Gaussian minimum shift keying (GMSK) modulation achieves a 1 Mbps symbol rate. Interference between Bluetooth and IEEE 802.11 can occur when the carrier power reduction due to interference from the transmitter leads to a decrease in carrier strength at the receiver. The carrier and interference levels can be calculated using factors such as the distance between the transmitter and receiver, the average density of transmitters in a specified area, the transmission power of the interfering system, and the signal attenuation coefficient influenced by propagation.

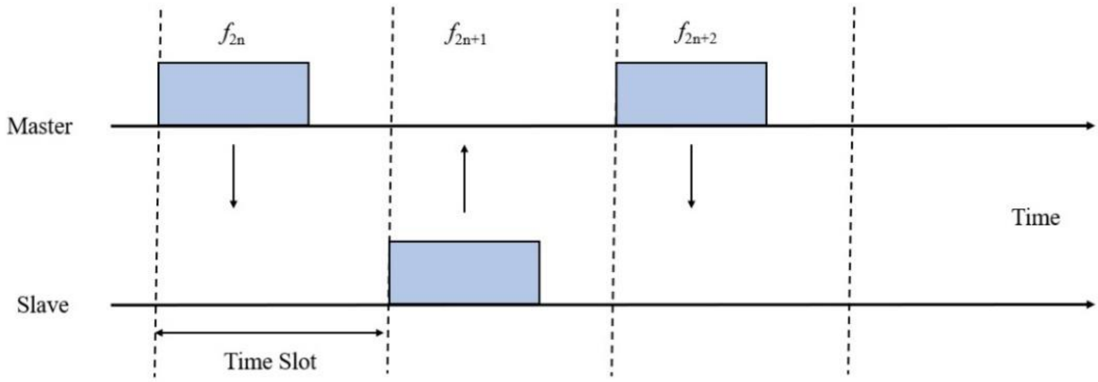

Figure 7. Frequency hop/time division transmission-reception on Bluetooth

In an IEEE 802.11 system using the DSSS method, excluding interference from outside the band, the probability of interference between Bluetooth and 802.11 on the same frequency is equal to the probability of Bluetooth hopping into the 22 MHz band of the 802.11 DSSS band. Additionally, when generating a Bluetooth hopping sequence, the process used to hop into the 802.11 band can be approximated as an independent distributed process with the parameter h_f. If the coexistence mechanism is not applied, the value of h_f is defined as 0.278 for Bluetooth with a 79 MHz band and 802.11 with a 22 MHz band [13], [14]. The average number of 1 Mbit/sec symbols involved in collisions between Bluetooth and 802.11 systems can be defined as shown in (1).

$$n_x = h_f(T_1^{(s)}\delta_1 + \sum_{i=2}^{N(x)-1} T_i^{(s)}\delta_i + T_{N(x)}^{(s)}\delta_{N(x)}) \quad (1)$$

In (1), $T_i^{(s)}$ represents the ratio of T_i/T_s (i = 1, 2, ..., $N(x)$) and T_s refers to the duration of the symbol. According to (1), to reduce the interference phenomenon between each system, the values of $N(x)$, h_f, and δ_i should be minimized. Although those values can be reduced by using shorter packets in 802.11, this method increases the overhead of data transmission via 802.11. Therefore, this paper proposes an algorithm that allows the coexistence of Bluetooth and 802.11 systems through traffic management techniques used in the MAC layer. This algorithm handles data transmission and reception, applies when the ACL link is active on the Bluetooth channel, and uses various packet lengths suitable for the Bluetooth system to avoid frequency overlap between Bluetooth and 802.11 data transmissions. In this paper, we assume that a Bluetooth communication device acting as the master, using a Bluetooth data link, detects that the frequency channel is occupied due to interference from the 802.11 system. Except for special cases, the 802.11 system does not exceed the available bandwidth of the 22 MHz band. In a non-cooperative setup, the Bluetooth communication device selects a channel based on observed packet loss, evaluates the received signal strength (RSSI) that can be received in the wireless environment before transmitting, and identifies the occupied frequency channels through trial packets. The Bluetooth communication device identifies the frequency channels by observing packet loss and detecting which frequency bands are affected by interference from the 802.11 system [11], [15]. The test packets that can be used are during the POLL-NULL data exchange between the master and slave communication devices. The master communication device starts transmitting data in even slots, while the slave communication device starts transmitting data in odd slots. For simplicity, we assume that a basic data packet is a single slot.

7. CONCLUSION

This paper discussed the increase in frequency bands used due to the advancement of wireless communication technologies, leading to the emergence of communication standards such as Bluetooth, Wi-Fi, and ZigBee, which are predominantly used in the ISM band. As a result, the number of communication standards operating in the same frequency band increases, leading to reduced availability of the band. Since these communication standards use the same frequency bands, mutual interference occurs. Therefore, this paper analyzes the mutual interference phenomena among wireless communication standards operating in the 2.4 GHz ISM band and proposes an algorithm used in traffic management techniques based on collision avoidance to reduce such interference.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Eugene Rhee	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
Junhee Cho		✓	✓	✓	✓	✓	✓	✓		✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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