Research on Airborne Wireless Sensor Network Based on Wi-Fi Technology

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Abstract. Due to the limitation of wired airborne communication network, it has become a trend to explore airborne wireless communication network. With the rapid development of wireless sensing technology, the International Telecommunication Union (ITU) issued the Wireless avionics Internal Communication (WAIC) standard. This standard is mainly used to detect the health condition and emergency of the internal and external structures of the aircraft. In this paper, based on the analysis of the research status of wireless airborne internal communication system at home and abroad, aiming at the internal structure of C919 narrow-body single-channel aircraft, a wireless communication scheme based on WI-FI technology and the corresponding wireless network architecture for the real-time monitoring of aircraft status in accordance with WAIC standards are proposed. The simulation results show that the wireless sensor network based on Wi-Fi technology is suitable for WAIC system.

Keywords: Wireless sensor network · The Wi-Fi technology · The network architecture · WAIC

1 Introduction

Safety and economy have always been the goal of civil aircraft. The development of electronic communication technology has greatly improved the degree of automation and safety of civil aircraft. Currently, various onboard electronic devices communicate via cable connections to the data bus. Cables are an important part of existing aircraft. The weight of cables and connectors between cables is about 2%–5% of the total weight of the aircraft, and the cable-related cost per aircraft is $2200 per kg [1]. The adoption of wireless communication can reduce the time and cost of cable wiring and installation. Studies show that about 30% of cables on airplanes can be replaced by wireless [1]. In addition, the WAIC system can support some new applications without the need for rewiring, and provides more opportunities to monitor more systems without adding weight to the aircraft. Wireless technology can also be used to monitor areas where cables cannot be executed, such as engine rotor bearing monitoring. Second, WAIC systems can also improve security. It is estimated that on average, more than 1077 missions

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were aborted due to wiring problems causing two aircraft fires per month [2]. In order to improve these aspects, using wireless communication system to replace part of wired communication is one of the development directions of the future aviation. Wireless avionics internal communication network refers to the wireless connection between two or more points on an aircraft, which does not provide air-to-ground, air-to-air communication [1]. For example, sensors mounted on the wings or engines can communicate with systems in the aircraft, etc. [3].

The key difference between WAIC network and ground wireless network lies in its different application requirements. Aircraft application environment is more complex and harsh, with higher requirements on reliability and safety [4]. In this paper, according to the application requirements of various electronic equipment in the aircraft, the appropriate wireless technology scheme and network architecture are selected to support airborne wireless communication, to provide theoretical and experimental verification for WAIC applications with high data rate, and to achieve the purpose of real-time monitoring of aircraft status.

2 Previous Work

In 2010, the world communication Congress (WRC-10) adopted the M.2197 standard *Technical Characteristic and Operational Objectives for Wireless Avionics Intra-communications (WAIC) report* [1], which mainly provides the technical characteristics and operational objectives of the WAIC system and identifies four different transmission modes for the WAIC network. They are high rate internal transmission mode (HI, High inside), high rate external transmission mode (HO, high outside), low rate internal transmission mode (LI, Low Inside) and low rate external transmission mode (LO, Low outside) [1]. The 2013 World Radiocommunication Conference (WRC-13) adopted report M.2283, which describes the application characteristics of WAIC networks and network spectrum requirements [8]. Since the release of WAIC system, industry and academia have carried out active exploration and research. WAIC is defined as a safety system for a new generation of aircraft. Both Boeing 737MAX and China C919 use wireless tire pressure and brake temperature measurement systems. In 2013, the Wireless Cabin Project began in Europe to develop in-flight wireless communication technologies, such as health monitoring systems for engines and landing gear. Then the NASA-organized FBW Consortium used wireless sensor technology on the LANDING gear of the B757 to complete a demonstration of an aircraft health monitoring system.

In academic circles, the research in recent two years mainly focuses on the combination of WAIC network and industrial wireless sensor network [3, 4, 5, 6, 7, 8] and the establishment of WAIC network communication model [9, 10]. In the literature [3], assessed the LTE MBB for high data rate WAIC application in the transmission of data rate, delay and reliability of the network performance, the results showed that MBB can meet the demand of communication, but its robustness in airborne environment technology is not enough, must improve robustness to meet under the environment of the airborne network resilience to random access interference. In reference [5], the network performance of the NB-IoT for low data rate WAIC applications was evaluated in terms of latency and reliability, and the results showed that the NB-IoT technology met the requirements of the WAIC system in a non-interference environment. However, in the case of aircraft interference, wireless technology must be discussed in the presence of interference to met WAIC system requirements. In literature [6], UWB technology is used to solve the wireless scheme of WAIC low data rate application, and UWB filter module is used in this scheme to conduct experiments. After evaluation and measurement, it is clear that the UWB filter bandwidth is well within the distance limit and can be applied to the WAIC system even with passenger influence. In reference [7], the performance and feasibility of LLDN, Wirelesshart, WISA and ISA100.11A in avionics applications were analyzed from the aspects of maximum allowable packet loss rate on the premise of flight. Literature [8] takes IEEE802.15.4 and IEEE802.11a/G standards as examples to analyze the media access mechanism of protocols, mainly including communication overhead and modulation efficiency. In reference [9], the experimental results of measuring the wireless channel of the WAIC system in a real aircraft interior environment are given, which show that the LOS environment is preferable to the Rayleigh fading channel and suggest the use of relay nodes to achieve the reliability of the wireless communication system. In literature [10], a model was established based on multiple factors including power factor, modulation efficiency and spectrum, and the technical characteristics of GMSK, QPSK, 16-PSK, 8-FSK and other modulation methods were analyzed in detail.

At present, there are few published papers on wireless aviation internal sensor network technology in China, and most of them are theoretical. Literature [11] analyzes the current research on airborne wireless communication in China, summarizes the research status of WAIC system, and analyzes the combination of WAIC system and industrial wireless sensor network on the basis of studying relevant foreign literature. Literature [12] proposed the communication protocol framework of WAIC network based on the general airborne network communication 5-layer model, and gave the future research direction.

3 Selection and Experimetion Evaluation of Wireless Technology

3.1 Choice of Wireless Technology

In order to meet the requirements of airborne wireless communication sensor network based on WAIC system, it is necessary to choose the wireless technology solution according to the structural characteristics of aircraft when constructing wireless network.

Airborne wireless communication network is mainly used to monitor the health status and emergencies of various parts inside and outside the aircraft. Therefore, different data transmission parts and data rates need to be distinguished during the construction of airborne wireless communication network. Only high data rate applications are considered in this paper, so only HI and HO applications are analyzed and evaluated.

At present, there are many kinds of wireless transmission protocols, such as NB-iot, Wi-Fi (IEEE802.11a/b/g), Zigbee (IEEE802.15.4), ISA100.11A and Bluetooth, etc. Different technologies have different characteristics and are suitable for different requirements and application scenarios. In this paper, bluetooth, Wi-Fi (IEEE802.11ax/g) and Zigbee (IEEE802.15.4) wireless technologies are selected for comparison. The reason is that bluetooth networking is simple and its power consumption is between Wi-Fi and

Zigbee. For Wi-Fi, it is suitable for big data and long-distance transmission. Zigbee has low power consumption, low cost and large network capacity. Table 1 gives a comparison of data rates between WAIC HI and WAIC HO applications and these three wireless technologies, for example: the data rate comparison between WAIC HI application and Wi-Fi shows that the data rate of Wi-Fi is 9.6 Gbps and the maximum data rate of WAIC HI application is 4.8 Mbps. Therefore, the data rate of Wi-Fi meets the requirements of WAIC HI application. Table 1 shows that Wi-Fi and Bluetooth meet the rate requirements for WAIC high data rate applications in terms of maximum data transfer rates.

Table 1. Comparison of data rates between wireless technology and WAIC requirements [13, 14, 15]

Wireless technology	WAIC HI	WAIC HO
Bluetooth	24 Mbps/4.8 Mbps	24 Mbps/1 Mbps
ZigBee	250 Kbps/4.8 Mbps	250 Kbps/1 Mbps
Wi-Fi	9.6 Gbps/4.8 Mbps	9.6 Gbps/1 Mbps

In the technical reports that have been submitted by the ITU, there is no direct requirement for delays in the WAIC system. Therefore, it is necessary to make reasonable assumptions based on wired transmission. In literature [16], the worst end-to-end delay calculation of external environment monitoring system in avionics wired network is 23.86 ms. From this calculated value, a reasonable assumption can be made. We can assume that the external application delay of HO is 10 ms to approximate the delay from the terminal node to the gateway node, so that 10 ms can be regarded as the reasonable delay requirement of HO application. For HI class, 0.5 s is considered to be a reasonable delay time, because HI class is mostly periodic data and monitoring data [2].

Table 2. Delay comparison between wireless technology and WAIC requirements [17, 18]

Wireless technology	WAIC HI	WAIC HO
Bluetooth	0.014 s/0.5 s	0.014 s/0.01 s
ZigBee	0.015 s/0.5 s	0.015 s/0.01 s
Wi-Fi	13.6 µs/0.5 s	13.6 µs/0.01 s

As you can see from Table 2, Wi-Fi meets WAIC system requirements in terms of latency requirements. After comparing the data rate and delay, it can be concluded that Wi-Fi technology meets WAIC system requirements. In addition, Wi-Fi is suitable for long-distance and big data transmission, which can avoid the disadvantages of channel congestion, communication delay and data loss caused by too many nodes to a certain extent. Therefore, Wi-Fi technology is more suitable for operation on airplanes.

3.2 Theoretical Evaluation

In terms of reliability, it can be reflected by the bit error rate. WAIC applications are known to have a bit error rate of 10^{-6} [1] according to the M.2197 standard proposed by the World Radiocommunication Congress, but this limit can be relaxed for some non-mission-critical applications. The calculation formula of ber is [2]:

$$\text{BER} = \frac{2}{log_2 M}\left(1 - \frac{1}{\sqrt{M}}\right) erfc\left(\sqrt{\frac{3log_2 ME_b}{2(M-1)N_0}}\right) \tag{1}$$

Where M is the number of modulation symbols and *erfc* represents the complementary error function. The E_b/N_0 of different modulation schemes can be calculated by formula (1). As shown in Table 3 below [3]:

Table 3. E_b/N_0 values of different modulation schemes

Modulation method	QPSK	16-QAM	64-QAM
E_b/N_0(dB)	10.53	18.74	23.53

The results obtained in Table 3 are converted into signal-to-noise ratio by the formula to study and analyze the performance of aircraft internal communication. According to the calculated E_b/N_0 value, the SNR value can be calculated as [3]:

$$\text{SNR} = \frac{E_b}{N_0} + 10log\frac{f_b}{B}dB \tag{2}$$

Where f_b is the total net average data rate in unit of *bps*. According to ITU-R M.2283-0 report [8], f_b of HI class WAIC application is 18.4 MHz, and that of HO class WAIC application is 12.3 MHz. B is the bandwidth in *Hz*. According to the above report, it can be concluded that the bandwidth of HI class WAIC application B is 40 MHz, and that of HO class WAIC application B is 65 MHz.

SNR values of different modulation schemes can be calculated according to Formula (2), and the calculated results are shown in Table 4:

Table 4. SNR values for high data rate applications under different modulation schemes

Modulation method	QPSK	16-QAM	64-QAM
SNR (HI/dB)	8.59	16.34	21.13
SNR (HO/dB)	2.96	11.72	16.51

It can be seen from Table 4 that the required signal-to-noise ratio is proportional to the modulation scheme. The results of these calculations theoretically indicate the reliability requirements for WAIC applications. Based on theoretical analysis, it can be seen that Wi-Fi technology can support the transmission requirements of all high data rate applications of WAIC.

3.3 Analysis of Simulation Results

In order to verify the feasibility of Wi-Fi technology in WAIC system, MATLAB software is used to simulate it. Packets are transmitted from a terminal device to a gateway node, which processes the packets and sends them to the backbone network. Vary the distance from the terminal to the gateway node to measure how far Wi-Fi technology can travel while ensuring reliability in the cabin environment. WAIC applications located inside the aircraft are somewhat affected by channel fading due to a non-line-of-sight path (NLoS) environment. For gateways and sensors placed outside the fuselage, the LoS condition is considered as there are no obstacles blocking the way. The SNR and SINR obtained under different transmission conditions are different from those of sensors placed internally, and should therefore be evaluated separately.

According to WAIC standard, the maximum transmission power of high data rate application is 30 dBm, the maximum path loss of HI application is 2.5 dB, and the maximum path loss of HO application is 2 dB [8].

The Wi-Fi core network consists of two computers and a wireless network card, EDUP AC1610. One computer is installed with a network adapter, which acts as a terminal node and sends high-data-rate packets, and one computer acts as a gateway node and receives packets. Network cable EDUP AC160 supports 2.4 GHz and 5.8 GHz. Because the 5.8 GHz band has less interference, it can effectively improve the wireless transmission rate and meet the requirements of high data rate avionics applications. The wi-fi channel bandwidth is set to 40 MHz. Interference signals are realized by software GNURadio [19]. During the experiment, the effect of different modulation order can be observed by changing the distance between two computers.

The first measurement is the transmission performance of WAIC HI application in Wi-Fi technology. There is no obstacle between the terminal node and the network management node, and it is in the straight channel of LoS position. The figure below shows the changes in SNR values measured using Wi-Fi technology to transmit data in the cabin interior environment. As shown in Fig. 1, Wi-Fi technology meets the operating requirements of HI applications over the entire transmission range without interference.

Next, when sending high data rate packets, interference signals are also sent, and obstacles are added between terminal nodes and gateway nodes for simulation. The interference signal is mainly RA signal. Radio Altimeters (RA) are high-transmitting power Radio devices that provide altitude measurements for aircraft and operate on the same spectrum as the WAIC system and are therefore a major source of operational interference for the WAIC system. Figure 2 shows the performance of Wi-Fi technology in the cabin in the presence of RA signal interference. As can be seen from Fig. 2, with the increase of transmission distance, SINR value decreases and transmission performance gradually decreases. High order modulation cannot meet the operating conditions of HI class applications. It can be seen from the figure that in the case of interference, the transmission distance of Wi-Fi technology for HI application is approximately limited to 9 m.

The difference between the results obtained in the experiment is due to the existence of interference. The cabin is a special transmission environment, which can also be regarded as a closed transmission environment. The production materials of the cabin, the seats in the cabin, and the movement of personnel are all sources of interference to

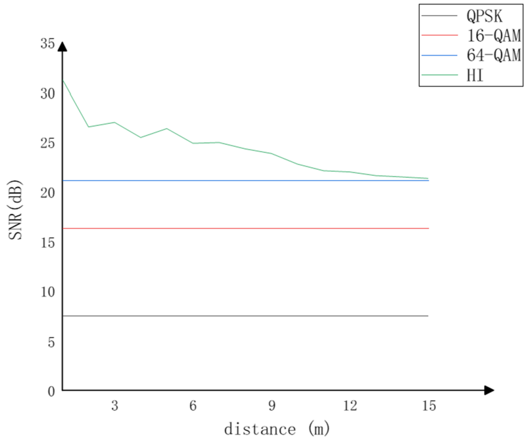

Fig. 1. SNR values measured in engine room environment

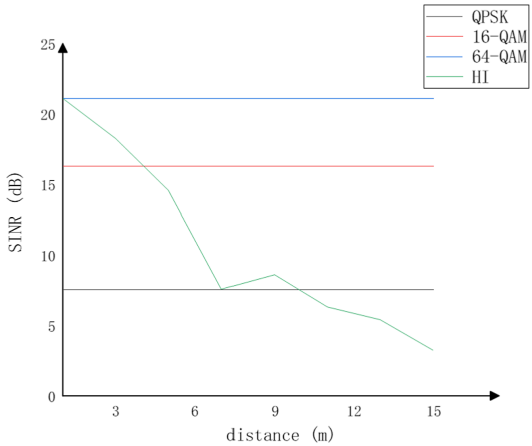

Fig. 2. SINR values measured in the presence of RA interference

wi-fi technology transmission. It can be seen from Fig. 1 and Fig. 2 that in the case of no interference, the SNR requirement can be met in the whole transmission range. When interference exists, high-order modulation cannot meet the SNR requirement, and when others meet the SNR requirement, the transmission distance is reduced to a few meters.

For HO applications, terminal nodes and gateway nodes are located in LoS environment to change the data transmission rate. The measured SNR values are shown in Fig. 3. It can be seen from the figure that Wi-Fi technology can meet the transmission performance of HO class and HI class in the case of no interference.

Figure 4 is the result obtained after adding interference signals, showing the transmission performance of Wi-Fi technology outside the cabin in the presence of interference, as shown in Fig. 4. In the flight of real aircraft, there are many interference signals outside the cabin and the interference ability is strong. Therefore, in the test, the transmission of

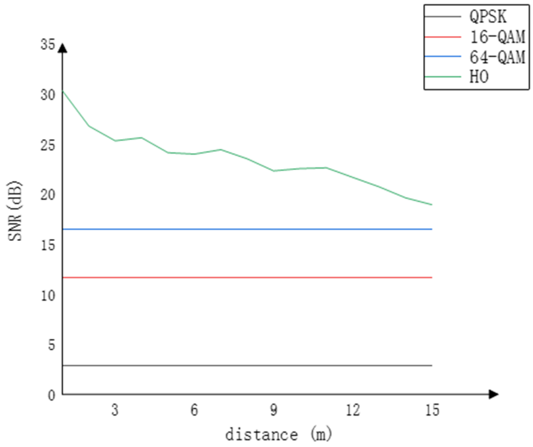

Fig. 3. SNR values measured in extravehicular environment

interference signals is increased to make it as close as possible to the real interference situation. It can be seen that in the presence of interference, the value of SINR decreases sharply as the distance increases. The transmission distance is limited to about 7 m.

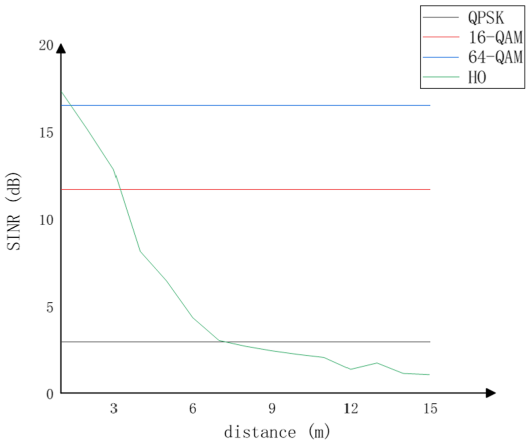

Fig. 4. Measured SINR value in the presence of RA interference

In conclusion, according to the experiments, when there is no interference, Wi-Fi technology can meet the SNR and data rate requirements of high data rate applications. However, when interference is introduced, the transmission performance will be severely degraded, so the transmission distance needs to be limited to meet the high data rate transmission requirements. The reliability of Wi-Fi technology can be achieved by changing the distance between the terminal and the gateway node. Through the above tests, the distance between the terminal node and the gateway node can be set to 7 m, which can meet the transmission performance requirements of HI and HO applications.

4 Hybrid Network Architecture

This section describes a network architecture based on Wi-Fi technology. The purpose of this network architecture is to replace the cables between terminals and AFDX switches, or gateway nodes, with wireless connections. Figure 5 shows a hybrid network architecture deployed in an aircraft. The sensor in the figure is responsible for collecting the monitoring data of the relevant position, and then transmits it to the gateway node (AFDX switch) through Wi-Fi wireless technology. After processing the data by the AFDX switch, the data is transmitted to the cab through the AFDX backbone network for the driver to view the data and analyze the health status of the monitored position.

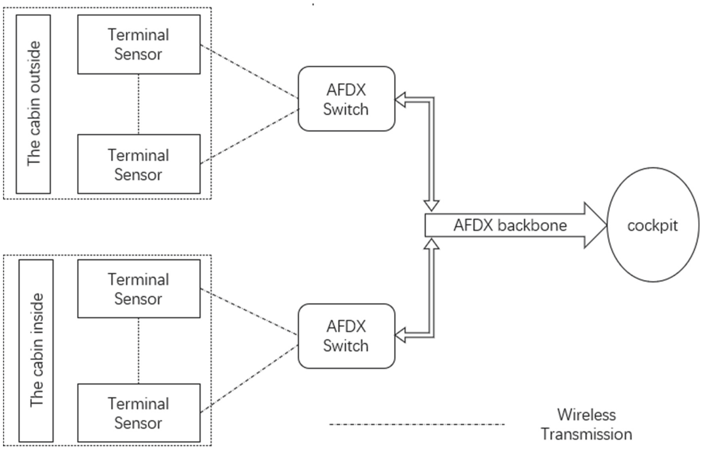

Fig. 5. Hybrid network architecture based on Wi-Fi technology

5 Conclusion

In this paper, airborne wireless sensor networks are studied. WAIC system provides a new method for airborne internal communication. This paper first evaluates the performance of three wireless technologies for high data rate wireless avionics internal communication (WAIC) applications. Through theoretical analysis and simulation experiments, wi-fi technology can meet the requirements of WAIC high data rate applications. In addition, the proposed hybrid network architecture based on Wi-Fi technology demonstrates the application scenarios of WAIC systems, which reduces cabling complexity in the cabin. Finally, the reliability of airborne wireless sensor network technology is analyzed. It can be concluded that wi-fi technology can also meet WAIC system requirements in the presence of interference. In the future, some methods can be studied to reduce transmission delay, and robust technology can also be considered to improve the recovery ability of the network in the presence of interference.

References

1. ITU-R. Technical Characteristic and Operational Objectives for Wireless Avionics Intra-Communications. Technical Report M.2197, Switzerland (2010)
2. Field, S., Arnason, P., Furse, C.: Smart wire technology for aircraft application. In: The 5th Joint NASA/FAA/DoD Conference Aging Aircraft, pp. 1156–1161 (2001)
3. Baltaci, A., Zoppi, S., Kellerer, W., et al.: Evaluation of cellular technologies for high data rate WAIC applications. In: IEEE International Conference on Communications, pp. 1–6 (2019)
4. Park, P., Di Marco, P., Nah, J., et al.: Wireless avionics intra-communications: a survey of benefits, challenges, and solutions. IEEE Internet Things J. **7**(99), 1–23 (2020)
5. Baltaci, A., Zoppi, S., Kellerer, W., et al.: Evaluation of cellular IoT for energy-constrained WAIC applications. In: IEEE 2nd 5G World Forum, pp. 359–364 (2019)
6. Baltaci, A., Zoppi, S., Kellerer, W., et al.: Wireless avionics intra-communications (WAIC) QoS measurements of an ultra wideband (UWB) device for low-data rate transmissions. In: 2020 AIAA/IEEE 39th Digital Avionics Systems Conference, pp. 1–10 (2020)
7. Park, P., Chang, W.: Performance comparision of industrial wireless networks for wireless avionics intra-communications. IEEE Commun. Lett. **21**(1), 116–119 (2017)
8. ITU-R. Technical Report M.2283, Geneva, Switzerland, December 2013
9. Bang, I., Nam, H., Chang, W., et al.: Channel measurement and feasibility test for wireless avionics intra-communications. MDPI Sens. **19**(6), 1294 (2019)
10. Suryanegara, M., Raharya, N.: Modulation performance in wireless avionics intra-communication (WAIC). In: The 1st International Conference on Information Technology, Computer, and Electrical Engineering. Semarang, Indonesia, pp. 597–604. IEEE (2014)
11. 范祥辉, 陈长胜, 史岩. 民用飞机无线航空电子内部通信网络技术综述. 航空工程进展 (09),129–135 (2020)
12. 李士宁, 范祥辉, 刘洲洲等. 无线航空电子内部通信网络协议现状与分析. 北京邮电大学学报 **44**(3), 1–8 (2021)
13. Lusky, I.: CAT vs NB-IoT-Examining the Real Differences. https://www.iot-now.com
14. Ouyang, G., Zhao, Y.: An application of IEEE802.15.4/ZigBee simulation model. In: 2016 3rd International Conference on Systems and Informatics (ICSAI), pp. 674–679 (2016)
15. IEEE. IEEE Technology Report on Wake-up Radio (2017)
16. Kang, K., Nam, M., Sha, L.: Worst case analysis of packet delay in avionics system for environment monitoring. IEEE Syst. J. **9**(4), 1354–1362 (2015)
17. IEEE. IEEE Standard for Low-Rate Wireless Network (2020)
18. IEEE. Wireless LAN Medium Access Control and Physical Layer Specifications (2020)
19. GNURadio. The Free & Open Software Radio System. https://www.gniradio.org/