Survey on Anti-jamming Technology of UAV Communication

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Abstract. Modern warfare is a five-in-one joint operation involving sea, land, air, air and electricity. Information weapons have become an important combat force. As the nerve center of UAV system, UAV data link is an information bridge connecting UAV with other information systems, command and control systems, weapon systems and so on. It is also a means to realize joint operations such as information communication and interoperation. In recent years, several military operations involving UAVs have shown that the UAVs data link can greatly shorten the time of reconnaissance, control, strike and evaluation, and has become an important means to improve combat effectiveness. At present, with the wide application of UAVs in military operations of various countries, unmanned systems are gradually developing from supporting combat equipment to main combat equipment, and countries are also developing anti-UAV means. UAV data links are faced with many challenges, such as shortage of spectrum resources, complex spectrum environment, serious environmental interference and human interference. Thus, higher requirements are put forward for its security, reliability and adaptability in complex environment.

Keywords: UAV · Data Links · Anti-jamming Technique

1 Introduction

Nowadays, the electromagnetic environment of battlefield is extremely complex, and the development of communication jamming equipment is rapid. For example, the EC2130 compass call communication electronic warfare aircraft jamming system operating frequency can reach 1GHz, power up to 5–10 kW, can suppress the enemy command and control network and air defense network; The Wolf pack system of the US Army mainly deals with frequencies-hop, low-power and networked communication systems. The working frequency band is 20 MHz–2.5 GHz. It uses small low-power and distributed equipment to destroy enemy communication networks through internal network interconnection technology. The distributed system which is close to and encircling the combat target is adopted to obtain the advantages of tactical power and detection sensitivity. Each distributed jamming point obtains the advantages of tactical radio frequency through internal networking. Therefore, in order to give full play to the role of data link, the anti-jamming ability of data link must be further improved.

A. Li et al. (Eds.): 6GN 2022, LNICST 504, pp. 111–121, 2023.
https://doi.org/10.1007/978-3-031-36011-4_10

Design of UAV data link more complicated than in other wireless communication system design, in terms of anti-interference of UAVs faces the challenge of the information transmission over a long distance caused the decline of the obstacles in the path loss, route of transmission, high-speed movement of unmanned aerial vehicle (UAV) doppler frequency shift and complex spectrum environment of interference and obstruction.

1.1 A Link Long Distance Path Loss

The most serious challenge of the UAV data link system is the long-distance transmission of information, which will bring the following challenges to the performance of the data link system:

(1) Power attenuation and spectral efficiency reduction. The wireless transmission link of IEEE802.11, also known as Wi-Fi, can only cover 100 m, while the later developed IEEE802.16, also known as WiMAX, can cover 3 km in rural areas and 1 km in urban areas. The above coverage range also applies to 3GPPLTE. General aviation data links require 360 km coverage, so the use of these traditional wireless communication links to implement long-distance measurement, control and transmission will cause serious power attenuation and extremely low spectral efficiency. Literature [8] shows that WiMAX network can achieve spectrum efficiency of 3 bps–5 bps/Hz in the range of 0.9 km. For long-distance transmission, the spectral efficiency will be even lower.
(2) Transmission delay. The long distance transmission of information will also cause serious delay of back and forth transmission time, which will greatly increase the communication protection time slot. Compared with the minimum delay of 17 μs for WiMAX networks over a range of 5 km, a one-way transmission of 360 km requires 1.2 ms.
(3) In addition, the long-distance transmission of information will increase the bit error rate of the system, reduce the signal to noise ratio of the receiver, and increase the probability of packet loss.

1.2 High Speed Movement of UAV Platform

The high speed movement of the UAV can bring Doppler frequency shift to the receiver, and the size of Doppler frequency shift is proportional to the speed of movement and inversely proportional to the wavelength. It can be calculated that the Doppler shift of L-DACS1 at 600 km/h and 1164 MHz is 1213 Hz, while the Doppler shift of WiMAX at 100 km/h and 2.5 GHz is 231.5 Hz. Because the frequency of electromagnetic wave is inversely proportional to the wavelength, the lower the working frequency band, the smaller the Doppler shift will be for the UAV moving at high speed. However, the spectrum resources in the low frequency band are very tight, so the Doppler shift brought by the high-speed movement of the UAV is a great challenge to the UAV data link.

1.3 Fading Caused by Obstacles in Link

The main frequency band of UAV data link application is microwave (300 MHz–3000 GHz), because microwave link has higher available bandwidth, but the microwave

frequency is high, the wavelength is very short, and there is no diffraction function. This characteristic of links creates the following communication challenges:

(1) Shadow fading. The obstacles encountered in the communication process of UAV data link can partially or completely block the signal transmission and cause serious shadow fading.
(2) Multipath fading. On a smaller scale, the receiver receives different phases of different copies of the same signal from different paths due to the scattering and reflection of electromagnetic waves through obstacles, resulting in multipath fading of wireless signals. Because the UAV data link is changing dynamically, the phase difference between replicas is also changing dynamically, so it is impossible to eliminate multipath fading by adding a fading overhead in traditional static wireless communication.
(3) In addition, multipath fading will cause serious symbol interference.

1.4 Human Non-malicious Interference and Malicious Interference

Non-malicious interference refers to the interference caused by the radio signals of other devices in the spectrum environment to the UAV data link. Such interference is superimposed on the signals transmitted in the communication channel, which distorts the original signal and leads to information error or loss. For example, when a signal with the same or similar frequency is generated in a circuit with different frequencies, intermodulation interference will occur. The malicious interference mainly exists in the military field, mainly the partial pressure type interference and deception type interference.

(1) Suppression interference refers to a kind of artificial communication interference in which the interference signal power continuously transmitted by the jammer is greater than the signal power of the UAV data link, so that the communication nodes in the data link cannot receive the radio frequency signal correctly, leading to the interruption of the communication link. According to the form of interference signal, clamped interference can be divided into three types: single frequency interference, narrowband interference and wideband interference. Since the clamped interference power swamps the desired signal or blocks the RF front end, its modulation information is irrelevant.
(2) To cheat interference with UAV data link using signal structure similar signals as a cheat, so can not detect induced receiver tracking capture deception signals, thus achieve the purpose of reduce its anti-jamming ability, and can be used with data link signal approximation power, avoid the excessive power be detected and reduced costs. In practical applications, such as the military field, the receiver is often faced with high dynamic, weak signal, strong interference or signal occlusion and other complex and variable environment, then the receiver will lose the lock to capture the deception signal or the influence of the deception signal increases in the tracking, and the whole system will be affected.

1.5 Crowded Spectrum Environment

Due to the shortage of spectrum resources, it is inevitably threatened by external interference signals. Traditional UAV data link uses HF, VHF and SATCOM frequency bands,

but SATCOM frequency band cannot guarantee that every data transmission stage can be used, and HF and VHF are becoming more and more crowded. In China, according to the frequency usage requirements of unmanned aerial vehicles issued by the Ministry of Industry and Information Technology, the frequency bands can be used: 840.5 MHz–845 MHz, 1430 MHz–1444 MHz and 2408 MHz–2440 MHz. Due to the shortage of spectrum resources, it is inevitably threatened by external interference signals. The modern UAV combat environment and combat mission are becoming more and more complex. The traditional anti-interference methods can no longer guarantee the high efficiency and reliability of the UAV data link communication. It is urgent to improve the anti-interference ability of the UAV data link in the complex electromagnetic environment under the limited spectrum resources.

To sum up, the use of unmanned aerial vehicle (UAV) to fight the implementation of the cluster, complex battlefield environment, bad data link communications facing enemy remote accurate fire fighting, electrical interference suppression and battlefield electromagnetic compatibility interacting multiple threats, such as to make the UAV can cluster anti-jamming communication under the complex battlefield environment, requires UAV data link system have the following abilities:

(1) Extensive spectrum management and allocation capabilities: available spectrum resources can be dynamically allocated to UAVs in any region and at any time;
(2) the ability to address large-scale power attenuation caused by long-distance transmission of information;
(3) the ability to avoid and avoid non-malicious interference;
(4) Ability to resist malicious interference: on the one hand, it is necessary to have strong anti-reconnaissance ability, which can reduce the probability of enemy reconnaissance system intercepting signals of UAV data link system through technical means such as concealing signal waveform, controlling transmission power and controlling transmission direction. On the other hand, in the process of system development, strong interference suppression, anti-interference modulation and adaptive filtering and other technologies should be fully adopted to improve the communication ability of strong resistance of UAV data link system under complex conditions, so as to effectively cope with various interference modes of targeting and arresting.
(5) Network survivability: Data link system should have good network topology and routing protocol design, as the key transmission network node paralysis of fire fighting or network attack, information network can according to the UAV flying position and the relationship between ground control site, automatically adjust the information communication nodes, to optimize the data link information transmission route, achieve against the dense deposit under the condition of communication;
(6) Capable of identifying friend or foe: in a complex confrontation environment, the enemy may take advantage of electromagnetic interference and suppression, and at the same time, use network intrusion, sending false instructions and other ways to remotely kidnap and control the UAV. Therefore, the identification function of friend or foe should be strengthened in the UAV data link system to prevent the false ground stations from pretending to be our ground control force to obtain the control authority of the UAV, or pretending to be our air formation combat force, so as to destroy and interfere with the scheduled combat plan of our formation.

2 Anti-jamming Technology (Mode and Principle)

In the future battlefield, the electromagnetic environment will be very bad, the situation of information warfare will be extremely complex. The difficulty of anti-interference ability lies in how to determine the interference spectrum and how to use the strategy to suppress it. In order to improve the anti-interference ability of UAV data link equipment, it is necessary to solve the interference caused by a variety of wireless signals, signal characteristics exposure, poor confidentiality and other problems. Multi-dimensional comprehensive anti-interference, anti-interception and anti-detection means are adopted to realize multi-dimensional anti-strong interference information transmission and distribution to cope with the future complex electromagnetic battlefield environment, and improve the reliability and persistence of UAV data link information transmission.

At present, the UAV data link USES a variety of anti-jamming technology, mainly including channel coding technology, spread spectrum technology, etc., and multiple input multiple output (MIMO) and orthogonal frequency division multiplexing (OFDM) technology, adaptive antenna technology and the emergence of cognitive radio (CR) technology, will also be the anti-interference ability of the UAV data link, provide strong technical support.

2.1 Channel Coding Technique

Due to interference or other reasons, there will be error codes during data transmission in the data link, so that the remote control instructions, telemetry parameters or images received by the receiver will be wrong. According to Shannon's channel coding theory, as long as the transmission rate of information is lower than the channel capacity, a channel coding method can always be found to make the error probability arbitrarily small. Therefore, the anti-interference ability of the data link can be improved by processing the data through channel coding.

The alternative channel coding methods mainly include convolutional code, BCH code, RS code, interleaved code and concatenated code. For example, the us army's Link16 data link adopts RS(31,16) coding in the information segment, and a 16bit supervision segment is added after every 15bit information segment, which can detect and correct 8 bit errors. When the Link16 data link is interfered with, the bit error rate of Link16 should be 0.45 at least, so that Link16 can not detect and correct the bit error and realize effective interference. According to the simulation results of Yang Guang et al., the modulation system with RS coding and interleaving has better anti-interference performance compared with the modulation system with RS coding and the modulation system without coding under the condition of partial frequency band interference, which can effectively ensure the reliability of datalinks message transmission [1]. The higher the complexity of channel coding, the longer the processing time of link equipment. Therefore, the channel coding of UAV data link should be designed by considering the requirements of transmission delay and anti-interference performance of UAV data link.

2.2 Spread Spectrum Technology

The basic principle of spread spectrum technology is that the transmitted signal is expanded to a very wide frequency band, which is much wider than the band width

of the transmitted information. The signal is recovered to the information bandwidth through correlation reception at the receiver. The basic principle can be expressed as

$$C = B\log_2\left(1+\frac{S}{N}\right) = B\log_2\left(1+\frac{S}{n_0 B}\right) \tag{1}$$

where, N is the noise power; S is the average power of the signal; B is the signal bandwidth; C is the channel capacity; N0 is the power spectral density of white noise. To improve the channel capacity C, it can be achieved by increasing the signal-to-noise ratio S/N or increasing the signal bandwidth B. However, there is a pairwise ratio between the signal-to-noise ratio S/N and the channel capacity C, so increasing the signal bandwidth B is more effective.

Spread spectrum technology is a widely used anti-jamming technology in US military datalink. It can be divided into direct sequence spread spectrum technology (DSSS), frequency hopping technology (FHSS) and time hopping technology (THSS) according to different ways of spreading spectrum.

2.2.1 Direct Sequence Spread Spectrum Technology

The working principle of DSSS system is shown in Fig. 1. At the origin, the spread spectrum code sequence with high bit rate is used to expand the spectrum at the origin, which reduces the power spectral density of the data link signal, makes it difficult for the enemy to detect it, and improves the anti-interference ability. In the receiving end with the same spread spectrum code sequence, interference and noise signal after the spread code sequence modulation, spectrum broadening, power spectral density reduction, spread spectrum signal after demodulation into a narrowband signal, power spectral density improvement, the gain of the system has increased several times, also improve the anti-interference ability of the system.

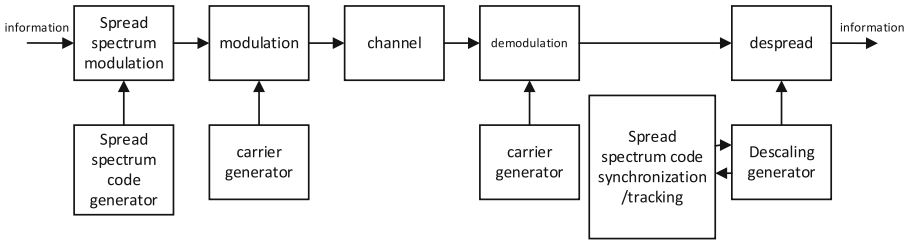

Fig. 1. Principle of direct sequence spread spectrum communication system

2.2.2 Frequency Hopping Technology

The working principle of the FHSS system is shown in Fig. 2. The spread spectrum code sequence signal is used for frequency shift keying modulation at the origin end to make the carrier frequency jump continuously, and the spread spectrum code sequence is used for signal recovery at the receiver end. In the time domain, the FH signal is a

multi-frequency shift keying signal. In the frequency domain, the FH signal jumps in a wide frequency band at unequal intervals. Compared with fixed frequency signal, as long as the enemy is not clear about the law of carrier frequency hopping, it is difficult to intercept our communication content, even if some frequency points are interfered by the enemy, it can still carry out normal communication on other frequency points that have not been interfered, so as to have good anti-interference ability.

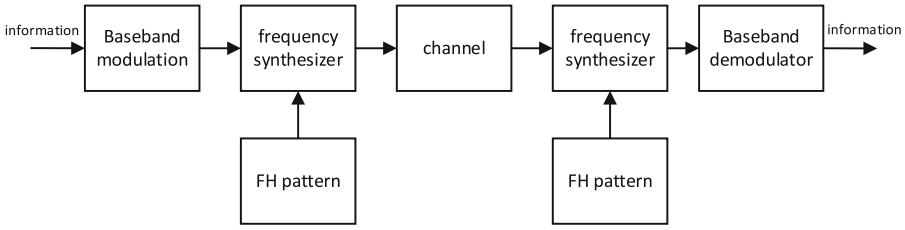

Fig. 2. Working principle of frequency hopping communication system

2.2.3 Time Hopping Technology

THSS is to make the transmitted signal jump on the time axis. The time axis can be divided into many time slices. Which time slice the transmitted signal in a frame is controlled by the spread spectrum sequence. Figure 3 is the basic block diagram of THSS system. The input data at the origin is stored first, and the on-off switch is controlled by the spread spectrum code sequence of the spread spectrum code generator. After two-phase or four-phase modulation, it is transmitted after RF modulation. At the receiving end, the IF signal output by the RF receiver is controlled by the locally generated spread spectrum code sequence which is the same as the origin, and then sent to the data memory and the output data after retiming through the two-phase or four-phase demodulator. As long as the receiving and receiving ends are strictly synchronized in time, the original data can be correctly recovered. Because the simple time-hopping method is not strong anti-interference, it is usually combined with other methods.

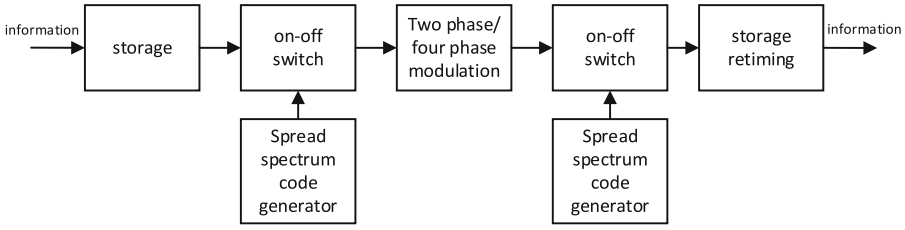

Fig. 3. Principle of time-hopping spread spectrum system

2.2.4 Combination Technology

Data link in the use of spread spectrum technology, usually adopt a combination of several spread spectrum methods. For example, American Link16 data link uses the combination technology of direct sequence spread spectrum, frequency hopping and time hopping, and CCSK code direct spread spectrum sequence with good autocorrelation performance. It hops 51 frequency points between 969 MHz and 1206 MHz at a rate of 77,000 times seconds, and each pulse symbol changes the carrier frequency once. However, the signal duration of each pulse is only the first 6.4 μs, and the hop time delay is up to 2.4585 ms [2]. This combination technique increases the difficulty of the synchronization technique. Both to complete the frequency hopping pattern synchronization. And to complete the spread spectrum sequence synchronization, and under the condition of know the characteristic of spread spectrum code sequence, by blocking interference with non-coherent PN code spread spectrum interference of modular interference, can effectively interference [3] to spread spectrum communication system, which leads to the defects of the current spread spectrum communication, therefore, it is necessary to develop a better spread spectrum sequence.

2.3 Multiple Input Multiple Output Technology

MIMO technology is an important communication technology emerging in recent years, which has attracted extensive attention. It refers to the wireless communication technology in which signals are transmitted through multiple antennas at the transmitter end and received by multiple antennas at the receiver end. MIMO technology, combined with OFDM and space-time coding, can achieve spatial diversity, time diversity and frequency diversity, and can achieve anti-interference in airspace, time domain and frequency domain. However, how to apply MIMO technology to anti-jamming technology of data link still needs to be studied on antenna configuration, power allocation and signal detection.

2.4 Orthogonal Frequency Division Multiplexing Technology

OFDM technology divides the channel into several orthogonal sub-channels, converts the high-speed data signals into parallel low-speed sub-data streams, and then modulates them to the sub-channels for transmission. Orthogonal signals can be separated by adopting correlation techniques at the receiver to reduce the mutual interference between sub-channels. The signal bandwidth on each subchannel is less than the correlation bandwidth of the signal, then each subchannel can be regarded as flat fading, so as to eliminate inter-symbol interference.

2.5 Adaptive Antenna Technology

At present, directional antenna technology is mostly used for anti-interference in UAV data link. Directional antenna means that the transmitted and received electromagnetic waves are particularly strong in one or several specific directions, while the received electromagnetic waves of the transmitter are 0 or minimal in other directions. The purpose

of anti-interference can be achieved by suppressing the reception of interference signals. The narrower the antenna beam, the stronger the concealment and the stronger the anti-interference ability.

Adaptive antenna technology using the principle of phased array antenna, the beam space filtering from all directions, it through to the antenna array element excitation adjustment, optimize the antenna array pattern, using the digital signal processing technology of jamming signal processing and recognition, in the direction of interference sources to form a beam of zero, restrain direction outside the reception, reduces the interference, At the same time reduce electromagnetic environmental pollution. The combination of spread spectrum technology and adaptive antenna technology is the main means of anti-jamming in American military satellite communication system.

The disadvantage of the adaptive antenna is that it forms a blind area in the zero-point direction, which affects the normal use of users in this area.

2.6 Cognitive Radio Technology

J.M itola puts forward the concept of cognitive radio, he thought the cognitive radio is an intelligent wireless communication system, through the study of the perception of the radio environment and active learning, real-time change communication system working parameters, such as encoding and modulation mode, working frequency and transmission power, dynamic testing and the use of idle spectrum, Adapt to changes in the external radio environment.

UAV data link can make use of cognitive radio technology monitoring communication frequency interference, according to the features of the interference signal, the real-time change the way data link channel coding and spread spectrum code sequence and frequency hopping pattern, jump way, the parameters such as power configuration, antenna model, the use of wireless spectrum resources reasonably, improve the information transmission ability and anti-interference ability.

3 Anti-jamming Technology of UAV Data Link

The anti-jamming technologies applied to UAV data link are mainly divided into three categories: related technologies to improve system reliability and effectiveness, based on cooperative communication technology and anti-jamming technology based on cognitive radio.

3.1 Improve Communication Reliability and Effectiveness

These related technologies include performance evaluation of multiple-input multiple-output (MIMO) systems [4, 5], information transmission strategies [6, 7], and the use of cellular systems and other wireless communication systems [8, 9]. Technical research focuses on physical layer and link layer are as follows:

(1) Integration of low-power MIMO systems.
(2) Research and use of anti-interference technology represented by spread spectrum and frequency hopping technology.

(3) Physical layer and MAC layer protocols and policies with high throughput and high reliability under limited spectrum resources.
(4) Integration of UAV data link system, satellite communication system and other wireless communication systems.

3.2 Based on Cooperative Communication

Literature [10] puts forward a cooperative communication method under the condition of multiple sources, and simulation results show that this scheme reduces the bit error rate of the received signal. Under the condition of dynamic transmission rate, the transmission reliability of the scheme is higher. The research of multi-source cooperative communication points out the direction of multi-link cooperative information transmission of UAV data link. Literatures [10] and [11] proposed the method of asynchronous cooperative information transmission on the basis of cooperative communication, and enhanced the reliability of information transmission from the physical layer (to build asynchronous cooperative transmission mode in 3D space) and the link layer (through multi-link cooperative forwarding protocol) respectively. The former makes full use of three kinds of spatial diversity technology in the physical layer, improves the diversity gain, and greatly improves the anti-interference ability. The latter can eliminate the influence of short-time link variation by single transmit multiple receive and bootstrap response algorithm based on random synchronous competition window at the link layer, obtain better network arrival rate and energy efficiency, enhance transmission reliability, and improve anti-interference ability. Literature [12] puts forward a relay selection method for cooperative communication under the outdated channel state information generated when the receiver and transmitter move relative to each other or the environment changes rapidly. Selecting the optimal relay can resist the interference to the cooperative communication system to a certain extent. Reference [13] proposed a channel state information prediction technology based on MAP criterion to improve the anti-interference ability of cooperative communication systems.

3.3 Based on Cognitive Radio

In addition, in order to solve the problem of spectrum resource shortage and the increasing difficulty of spectrum management with the widespread use of UAVs, cognitive radio technology for spectrum sensing and system reconstruction of UAVs is studied. Literature [14] proposes a prediction and evaluation method combining support vector machine and power criterion for the interference degree of UAV data link in the complex environment composed of geographical environment, meteorological environment, electromagnetic environment, etc. The predicted results can be used for the reconstruction of UAV data link. On the basis of analyzing the current problems of UAV data link, literature [15] puts forward the concept and connotation of UAV intelligent data link based on cognitive radio, describes the working process, and gives the index system and function classification of UAV intelligent data link. Based on the function of UAV data link, the architecture of UAV intelligent data link is put forward. Literature [16] proposes a multi-parameter planning method for UAV data link based on state machine, which provides a feasible and effective idea for the reconstruction of UAV data link.

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