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ATG spectrum analysis and interference mitigation for intelligent UAV IoT

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Abstract

As UAV Internet of things applications continue to grow, so does interest in the development of air-to-ground (ATG) systems, which can effectively expand communication system coverage. To maximize utilization of frequency resources, the ATG system adopts frequency reuse with the 5G system on the ground. This research studies the co-channel interference between ATG and 5G at 3.5 GHz as well as the neighboring channel interference with C-band fixed satellite service. We do research on various ATG aircraft flying altitudes and horizontal distances, which yields multiple potential interference reduction strategies. Finally, numerical results are shown to demonstrate the efficacy and productivity of our proposed methods.

Keywords: Internet of things (IoT), Air-to-ground (ATG) system, Unmanned aerial vehicle (UAVs), Interference analysis

1 Introduction

The Internet of things (IoT) has emerged as a crucial component of the next generation of information technology [1]. The features of borderless communication permit IoT technology to communicate instantaneously with anything, independent of time, location, or user. Faced with diverse application requirements in the future Internet of things, mobile communication systems realize network interconnection via aircraft airborne equipment and ground facilities, which can more efficiently utilize frequency resources, expand service range, and enhance user experience [2].

With the advance in technology, IoT applications require higher data rates, large bandwidth, increased capacity, low latency and high throughput. The ultimate goal of IoT technology is to introduce plug-and-play technology that makes life easier for the end user. Currently, for individuals, IoT technology plays a pivotal role, for example in the form of e-health, smart devices to improve living standards. IoT also has a large number of applications in automation, smart supply chain and transport, remote monitoring and logistics. Unmanned aerial vehicles (UAVs), also commonly referred to as drones, have attracted a great deal of attention in the last decade due to their applications in aerial imaging, cargo transportation and IoT. At the same time, UAVs equipped with advanced transceivers and high-capacity batteries are becoming increasingly popular in ATG communication systems, which offer high maneuverability and the flexibility of on-demand deployment. In particular, the introduction of UAV technology has effectively facilitated the possibility of air-to-ground (ATG) communications that many wireless service providers have introduced plans for UAV-related applications. UAVs are also valued in ATG communication systems for their high maneuverability, flexible deployment and low cost.

Driven by information technology and communication technology, the Internet of things in the air has also shown vitality and vigor. With the arrival of the era of "mobile phone on the air" of civil aviation of China, passengers' demand for Internet access in the air is increasingly strong. There are mainly two ways to access the Internet in the air, one is satellite communication [3], and the other is ATG broadband communication [4]. Satellite communication has the advantage of wide coverage, which can fully cover the ocean, desert or transnational flight. As ATG communications have a wider coverage on the continent, ATG technology is more developed in some countries where domestic aircraft transport is more developed, such as China, the USA and Australia. The coverage of ATG is sufficient to meet most application scenarios. Moreover, ATG has the advantages of high data bandwidth, large capacity, low delay and low cost. Therefore, compared with the satellite access scheme that is more suitable for transnational and transoceanic routes, the scheme of accessing the ground private network through the aircraft-borne communication equipment has the advantages of low transformation cost, fast speed and small delay and will become the mainstream mode for domestic flights to access the Internet.

ATG is a ground-to-air communication technology that makes it possible for airplanes to have Internet connection. ATG carries out tailored development for the qualities of high-speed aircraft movement and broad coverage using established land mobile communication technologies [5], such as 5G. It creates a specialized network for ground-to-air 3D coverage and a dedicated base station with an antenna that can cover the sky, addressing the problem of high-altitude 3D coverage and enabling high-speed data transfer between the ground and the air. The plan for ground-based stations is in line with the advancement of mobile communication technology and offers low-cost, high-bandwidth, high-traffic solutions. It offers several benefits for setting up, maintaining, and upgrading networks. The use of ground-to-air broadband communication systems will have a significant influence on passenger service and operational safety in civil aviation. ATG service has a wide range of industrial application prospects, including healthcare rescue, flight operation, air climate and flight safety laws of airlines, intelligence of air traffic control departments, digital air traffic control applications, ground distant industrial control applications, etc. ATG service can provide on-board entertainment, on-board office and customized services for air passengers.

In the past 30 years, the progress of mobile communication technology has brought great changes to our work and life [6]. The ATG is customized and developed for the characteristics of fast aircraft movement and wide coverage. At present, there are several typical ATG broadband communication systems in use in the world. Among them, Gogo air of the USA is the first ground-to-air broadband operator in the world to provide services for civil aircraft. It has been in commercial use for 9 years and is evolving to 5G, and can provide a peak experience rate of more than 100Mbps. The European air network (EAN) uses the combination of the ATG system and satellite system to provide on-board communication coverage to Europe. At present, the system has deployed more than 300 base stations [7]. China's ATG broadband communication system is currently under construction [8], which is expected to provide a higher peak rate.

The main reason for ATG to become the mainstream is that under the same coverage area of land routes. ATG has larger bandwidth, lower cost and better experience. In the past development of ATG system, some studies have carried out interference analysis and evaluation between ATG system and terrestrial mobile communication system. However, up to now, there is no relevant research conclusion on the same frequency interference analysis of ATG system and 5G system [9].

Taking into account the scarcity of frequency resources and improving the utilization rate of the allocated spectrum, the ATG system adopts the same frequency network as the terrestrial 5G system. This paper endeavors to avoid the interference caused by the frequency reuse between ATG system and ground mobile communication system, as well as reduce the stray interference caused by the ATG FSS to the adjacent frequency satellite. Specifically, we analyze the interference from 5G ATG airborne customer premise equipment (CPE) to ground 5G system base station and the adjacent frequency satellite earth station in 3.5 GHz frequency band.

The remainder of the paper is organized as follows. Section 2 introduces our system model with a detailed configuration of distinct interference analysis scenarios, including ATG system, 5G system, FSS and the propagation model adopted by the interference link. Section 3 presents the co-frequency interference analysis between ATG and 5G, whereas Sect. 4 gives adjacent frequency interference analysis between ATG and satellite services. Section 5 introduces the AI-based interference cancellation method. Finally, Sect. 6 concludes the paper.

2 System model

ATG system consists of ATG ground base station and ATG airborne CPE. The flight height of the airborne terminal of the ATG system is set to 3–10 km, and the radius of the ATG service area is 100 km. Since the ATG system adopts the same frequency network as the ground 5G system, the airborne Ground-to-ground emissions from ATG airborne CPEs have the potential to cause harmful interference to existing ground-deployed systems. Through the analysis of the services near the working frequency band of the ATG system, it is found that the 5G system and the ATG system coexist on the same frequency, and the C-band FSS system and the ATG system coexist on the adjacent frequency. So in this paper, the interference of ATG airborne CPE with different flying heights and different cell positions to the same frequency ground 5G system base station and the adjacent frequency FSS receiving satellite earth station using 3.5 GHz band transmission is studied. The composition of ATG system and possible interference scenarios are shown in Fig. 1 [10].

2.1 ATG system airborne terminal parameters

According to the actual deployment of the ATG system, the parameters of the ATG airborne terminal involved in the same frequency interference compatibility analysis are presented in Table 1. The maximum transmission power of the airborne CPE

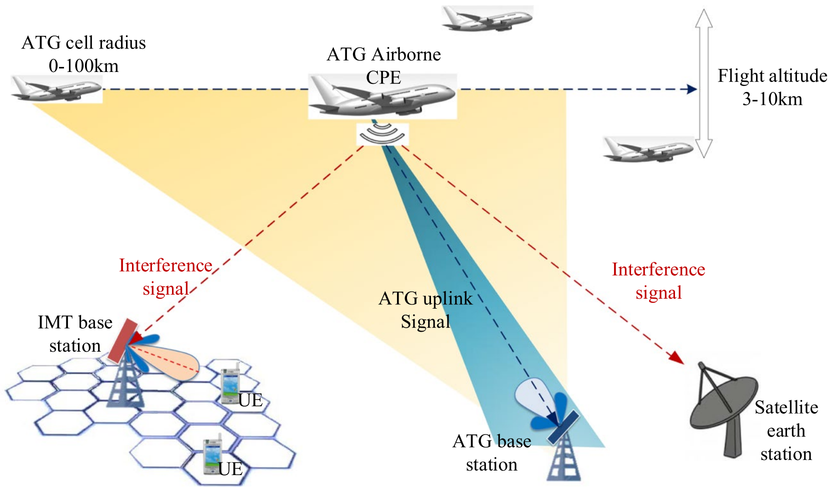

Fig. 1 Schematic diagram of airborne CPE uplink interference in ATG system

Table 1 ATG airborne terminal parameters

Parameter	Value
Frequency band	3500 MHz
Network configuration	TDD
Channel bandwidth	100 MHz
ATG area radius	100 km
Maximum transmitting power	26 dBm
Element gain	5 dBi
Antenna altitude	3–10 km

Table 2 General NR spectrum emission mask

Δf_{OOB} (MHz)	Channel bandwidth (MHz)/Spectrum emission limit (dBm)			Measurement bandwidth
	5	10, 15, 20, 25, 30, 35, 40, 45	50, 60, 70, 80, 90, 100	
±0–1	− 13	− 13		1% of channel BW
±0–1			− 24	30 kHz
±1–5	− 10	− 10		1 MHz
±5–6	− 13			
±6–10	− 25			
$\pm 5\text{-}BW_{Channel}$		− 13		
$\pm BW_{Channel}\text{-}(BW_{Channel}+5)$		− 25		

terminal is 26dbm, the gain of the single array element of the airborne phased array antenna is 5 dBi [11], and the maximum antenna gain is 20.0515 dBi. The flight height of the ATG UAVs is 3–10 km. The out of band and out-of-band useless transmission indexes of 5G ATG terminals can be determined according to Table 6.5.2.2-1 of 3GPP TS 38.101-1. The specific requirements are given in Table 2.

2.2 5G mobile communication system parameters

The parameters of the 5G mobile communication system involved in the compatibility analysis, including base station deployment, antenna type, interference protection standard, etc., refer to Annex 4.4 to Document 5D/716-E of ITU WP5D chairman's report [17]. The parameters of the 5G mobile communication system are given in Table 3. In the rural scenario, the antenna height of the 5G system base station is 35 m, the maximum gain of a single array element is 6.4 dBi, the antenna dip angle is 3°, and the receiver protection threshold is − 115dBm/MHz. In the urban scenario, the antenna height of the 5G system base station is 20 m, the maximum gain of a single array element is 6.4 dBi, the antenna dip angle is 6°, and the receiver protection threshold is – 115 dBm/MHz. According to ITU-R M.2101 [12], the maximum antenna gain is 24.46 dBi.

2.3 Fixed satellite service (ATG) system parameters

The system parameters of FSS earth station are given in Table 4. The operating frequency band of C-band satellite fixed service (ATG) is 3700–4200 MHz, and the elevation angles of satellite earth stations are 15°/30°/45°. In the rural scenario, the antenna height of the FSS satellite earth station is 3 m, the antenna diameter is 1.8 m, and the maximum gain of the antenna is 35.7 dBi. In the urban scenario, the antenna height of FSS satellite earth station is 10 m, the antenna diameter is 2.4 m, and the maximum antenna gain is 38.2 dBi.

According to ITU-R S.2199-0 report [13], when the receiving saturation interference threshold of satellite earth station is 60 dBm, the interference protection criteria (I/N) of the satellite earth station refer to ITU-R S.1432-1 proposal [14]. The interference signal

Table 3 5G mobile communication system parameters

Parameter	Value	
Frequency band	3500 MHz	
TDD/FDD	TDD	
Typical channel bandwidth	100 MHz	
Scenario	Rural	Urban
Element gain	6.4 dBi	6.4 dBi
Mechanical down-tilt	3°	6°
Antenna height	35 m	20 m
Cell radius	1.6 km	0.4 km
Sectorization	3 sectors	
Antenna pattern	Recommendation ITU-R M.2101[12]	
Horizontal/vertical 3 dB beam width of single element	90° for H 65° for V	
Horizontal/vertical front-to-back ratio	30 dB	
Antenna polarization	±45°	
Antenna array configuration	4 × 8	
Array ohmic loss	2 dB	
Protection criterion (I/N)	− 6 dB	
Noise temperature	290 K	
Receiver noise level (10logKT B)	− 109 dBm/MHz	
Noise figure	5 dB	
Receiver protection threshold	− 115 dBm/MHz	

Table 4 Fixed satellite service parameters

Parameter	Value	
Frequency band	3700–4200 MHz	
Antenna pattern	ITU-R S.465[18]	
Elevation angle	15°/30°/45°	
Scenario	Rural	Urban
Antenna diameter	1.8 m	2.4 m
Antenna height	3 m	10 m
Peak antenna gain	35.7 dBi	38.2 dBi
Blocking indicator	− 60dBm@100 MHz	
Protection criterion (I/N)	I/N = − 12.2 dB (ITU-R S.1432–1)	
Noise temperature	100 K	
Receiver noise level (10logKT B)	− 118.6 dBm/MHz	
Receiver protection threshold	− 130.8 dBm/MHz	

limit of the satellite earth station is 12 dB less than the noise power of the satellite earth station receiving system under clear sky conditions. Therefore, the interference protection threshold of the satellite earth station is − 130.8 dBm/MHz.

2.4 Propagation model of interference link

When considering that the ATG airborne CPE terminal interferes with other systems of the same frequency or adjacent frequency, due to the flight height of the aircraft, the calculation method of the propagation loss uses the free-space propagation model of ITU-R P.525 and ITU-R P.2108 ground-to-air path clutter loss [15, 16], where 50% of the location percentage is selected.

3 Interference evaluation method for co-frequency

3.1 Scenario of co-frequency interference

The ATG airborne CPE terminal operating in the 3.5 GHz band may interfere with the reception of the ground 5G mobile communication system base station with the same frequency because it is multiplexed with the ground 5G. Therefore, it is necessary to conduct compatibility research with the 5G system. In the process of interference analysis [19, 20], it is assumed that there is an aircraft using the ATG system in the air. Considering the worst scenario that the uplink transmission of the aircraft's airborne CPE will cause interference to the 5G base station of the same frequency on the ground, that is, the main lobe direction of the ATG Airborne CPE antenna faces the direction of the antenna panel of the 5G base station. The schematic diagram of the same frequency interference scenario is shown in Fig. 2.

3.2 Deterministic analysis method

For the co-channel interference between the ATG airborne terminal and the reception of 5G base station, a deterministic calculation method can be used to achieve the maximum isolation required for system coexistence. Specifically, the isolation degree can be obtained by the following:

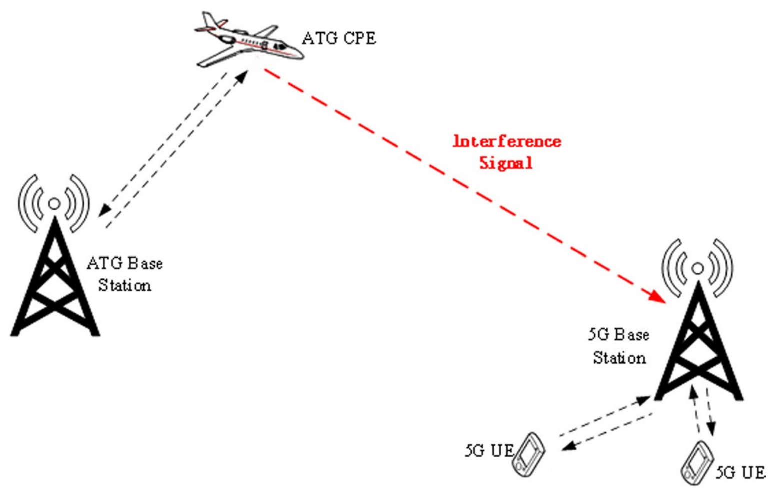

Fig. 2 Earth-space clutter loss between ATG and other systems

$$\text{Isolation} = P_{\text{TX}} - L_{\text{RX}} - \text{MCL} - L_{\text{ces}} - I_{\text{RX}}^{\text{max}} \tag{1}$$

where P_{TX} represents the interference system transmitting power and L_{RX} is the array ohmic loss of the interfered system. MCL is the minimum coupling loss as follows,

$$\text{MCL} = \text{Loss} - G_{\text{TX}} - G_{\text{RX}} \tag{2}$$

where G_{TX} and G_{RX} are the antenna gain of the interfering system and the interfered system, respectively. The Loss represents the free-space path loss, which is given by

$$\text{Loss} = 32.4 + 20 \times \log(d) + 20 \times \log(f) \tag{3}$$

where d is the straight-line distance between the two systems and f is the carrier frequency.

The Earth-space clutter loss L_{ces} in Eq. 1 is obtained with reference to Recommendation ITU-R P.2108 [16]; the clutter loss not exceeded for p% of locations L_{ces} for the terrestrial to airborne path is given by:

$$L_{\text{ces}} = \left\{ -K_1 \left[\ln\left(1 - \frac{p}{100}\right) \right] \cot\left[A_1 \left(1 - \frac{\theta}{90}\right) + \frac{\pi\theta}{180} \right] \right\}^{\left[\frac{0.5(90-\theta)}{90}\right]} -1-0.6Q^{-1}(p/100) \tag{4}$$

$$K_1 = 93\left(f^{0.175}\right)$$

$$A_1 = 0.05.$$

where $Q^{-1}(p/100)$ is the inverse complementary normal distribution function and the elevation angle θ is the angle of the airborne platform as seen from the terminal.

The maximum interference allowed by the interfered system $I_{\text{RX}}^{\text{max}}$ in Eq. (1) can be calculated by the following formula:

$$I_{RX}^{max} = N_{Noise} + \frac{I}{N} \quad (5)$$

where I/N is the interference threshold of the interfered system and the natural noise floor N_{Noise} of the receiver of the interfered system is given in the following equation:

$$N_{Noise} = -174 + NF + 10 \times \log(Receive_{BW}) \quad (6)$$

where NF and $Receive_{BW}$ represent the noise factor and channel bandwidth of the interfered system, respectively.

$$I/N = 10 \times \log\left(10^{\frac{R}{10}} - 1\right) \quad (7)$$

where R is the sensitivity deterioration margin.

3.3 Deterministic calculation results

In this section, deterministic computational coexistence analysis is performed for two typical base station deployment scenarios in 5G networks: urban macro and suburban macro. The interference system 3.5 GHz ATG airborne CPE transmit power is 26 dBm, and the maximum gain of the antenna is 20.0515 dBi. The propagation model uses the free-space propagation model and ITU-R P.2108 clutter loss [16]. The antenna model of the base station of the disturbed 5G system adopts ITU-R M.2101 proposal [12], and the analysis scenarios are urban scenario (antenna down-tilt angle: 6°) and rural scenario (antenna down-tilt angle: 3°), the maximum antenna gain is 24.46 dBi. In different scenarios, the flight altitude of ATG aircraft is set to 3 km and 10 km, respectively, and the calculation of the additional isolation of interference is presented in Table 5 for different horizontal distances between ATG aircraft and 5G base stations.

Table 5 Deterministic calculation conclusion

Horizontal distance from 5G base station	Additional isolation of ATG from terrestrial 5G networks			
	Urban		Rural	
	Flight altitude 3 km	Flight altitude 10 km	Flight altitude 3 km	Flight altitude 10 km
km	dB	dB	dB	dB
1	4.93143	− 54.805	9.61994	− 34.722
2	19.1081	− 21.496	20.0354	− 13.083
3	11.3066	− 9.0845	0.53831	− 3.7104
5	20.1008	4.3881	16.6711	7.11284
10	16.9857	0.84904	16.6325	− 9.9193
20	− 10.586	1.24114	8.10651	− 3.3721
30	0.0529	6.71194	6.1429	8.57824
40	− 2.0721	4.10925	2.82218	0.55205
60	− 8.0917	− 18.902	− 4.8410	− 3.6719
80	− 10.586	− 13.513	− 7.3351	− 2.6933
100	− 15.843	− 10.405	− 13.218	− 4.3147

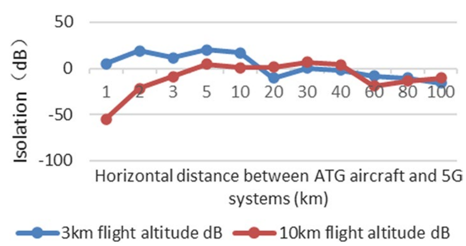

Fig. 3 Additional isolation required for coexistence of ATG and 5G systems (urban scenario)

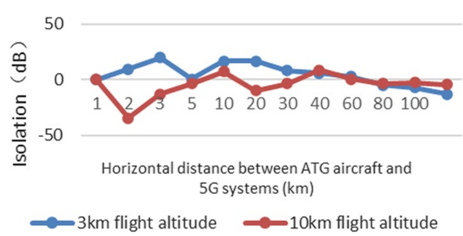

Fig. 4 Additional isolation required for coexistence of ATG and 5G systems (rural scenario)

Considering the scenario of ATG airborne CPE co-channel interference with 5G mobile communication system base station reception. The deterministic calculation results of interference isolation degree in Table 5 show that the additional isolation required for the two systems differs significantly for different scenarios, different horizontal distances, and different flight altitudes.

In the urban scenario, the ATG system aircraft flying at an altitude of 3 km, the two systems need an additional isolation of 0.05–20 dB to prevent interference. When the flight altitude of the ATG system aircraft is 10 km, an additional isolation of 0.85–6.7 dB is required to prevent interference. In the rural scenario, when the ATG system aircraft fly at 3 km, the two systems need additional isolation of 0.54–20 dB to not cause interference, and when the ATG system aircraft fly at 10 km, additional isolation of 0.55–8.58 dB is needed to not cause interference.

In urban scenarios and rural scenarios, at different flight altitudes, the relationship between the additional isolation required by the 3.5 GHz ATG system and the 5G system and the variation of the ATG at different horizontal positions of the cell is shown in Figs. 3 and 4.

According to the analysis of Figs. 3 and 4, the following can be concluded. In the same scenario, considering the worst case of the ATG airborne CPE antenna facing the ground 5G base station, the higher the flight altitude of the ATG system aircraft, the effective reduction in the additional isolation required for the coexistence of the ATG system and the 5G system, which means the coexistence between systems will be easier. At the same flight altitude, when the ATG aircraft flies from the countryside to the city, the position of the maximum interference point between the ATG system and the 5G system is closer to the disturbed base station.

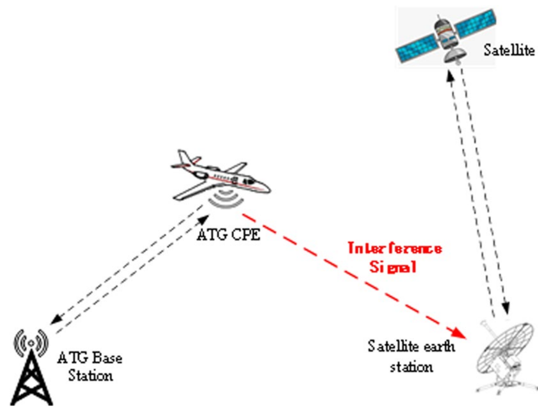

Fig. 5 Earth-space clutter loss between ATG and other systems

4 Interference evaluation method for adjacent frequency

4.1 Study scenarios

The ATG airborne CPE terminal operating at the 3.5 GHz band may interfere with the reception of the C-band adjacent frequency satellite earth station. In the process of deterministic calculation and interference analysis, it is assumed that there is an aircraft using the ATG system in the air. Considering the worst scenario that the uplink transmission of the aircraft's airborne CPE interferes with the reception of the FSS satellite earth station, that is, the ATG airborne CPE interference signal falls into the main lobe of the satellite earth station. The schematic diagram of the same frequency interference scenario is shown in Fig. 5.

4.2 Deterministic analysis method

For the reception of fixed service earth station of C-band adjacent frequency 5G satellite transmitted by the ATG airborne terminal, the deterministic calculation method can be used to carry out research and calculate the maximum isolation required for coexistence between systems. Considering the possibility that the uplink signal of the ATG airborne terminal interferes with the main beam of the adjacent frequency satellite earth station, the worst scenario in which the ATG airborne signal is aligned with the ground satellite earth station is considered. Wherein the isolation degree can be expressed by the following formula:

$$\text{Isolation} = \text{OOBlevel} - \text{MCL} - \text{Loss}_{\text{Polarization}} - L_{\text{RX}} - L_{\text{ces}} - I_{\text{RX}}^{\max} \tag{8}$$

where OOBlevel represents the out-of-band unwanted emission indicator of interference system. $\text{Loss}_{\text{Polarization}}$ is the polarization loss, and L_{RX} is the feeder loss of the interfered system. The Earth-space clutter loss L_{ces} and the maximum interference allowed by the interfered system $I_{\text{RX}}^{\max}$ are given by Eqs. (4) and (5), respectively. The minimum coupling loss can be expressed as

$$\text{MCL} = \text{Loss} - G_{\text{TX-element}} - G_{\text{RX-max}} \tag{9}$$

where the Loss represents the free-space path loss, which can be shown as Eq. 3. $G_{\text{TX-element}}$ and $G_{\text{RX-max}}$ are the element gain of the interfering system and maximum antenna gain of the interfered system, respectively.

When the total power of the jamming signal of the ATG airborne uplink transmitted signal received by the satellite earth station exceeds a certain value, the saturated interference may cause the satellite earth station to fail to work normally. Blocking interference isolation I_{Block} is calculated as follows.

$$I_{\text{Block}} = P_{\text{TX}} + G_{\text{TX}} + G_{\text{RX-max}} - \text{Loss} - \text{Loss}_{\text{Polarization}} - L_{\text{RX}} - L_{\text{ces}} - E_{\text{Block}}, \quad (10)$$

where P_{TX} represents the interference system transmitting power. G_{TX} and $G_{\text{RX-max}}$ are the antenna gain of the interfering system and maximum antenna gain of the interfered system, respectively. $\text{Loss}_{\text{Polarization}}$ is the polarization loss. And L_{RX} is the feeder loss of the interfered system. The free-space path loss Loss and the Earth-space clutter loss L_{ces} are given by Eqs. (3) and (4), respectively. E_{Block} is the satellite earth station blocking interference index.

4.3 Geographic isolation

In this section, a deterministic calculation compatibility analysis is carried out for the 3.5 GHz ATG airborne CPE to interfere with the reception of adjacent frequency satellite earth stations in two typical scenarios, urban and rural. According to Table 2, it can be seen that when the frequency interval between the two systems is larger than 100 MHz, the out-of-band transmit power of the 3.5 GHz ATG airborne CPE of the interference system is – 25 dBm/MHz, the single-antenna array element gain is 5 dBi, and the flight height of the ATG aircraft is set to 3 km and 10 km. The propagation model adopts the free-space propagation model and ITU-R P.2108 ground-to-air clutter loss [16]. Considering the worst case that the ATG airborne uplink signal is facing the disturbed adjacent frequency satellite earth station, in urban and rural scenarios, satellite earth stations with different elevation angles use the maximum antenna gain of 38.2 dBi and 35.7 dBi, respectively. The calculation of the additional isolation degree of interference is presented in Table 6.

In the deterministic calculations for Table 6, the adjacent frequency interference from the ATG airborne terminal to the reception of the FSS satellite ground station is considered (Table 7).

Table 6 Deterministic calculation conclusion—urban

ATG out-of-band unwanted emission	dBm/MHz	− 25		
ATG antenna element gain	dBi	5		
Scenario		Urban		
FSS earth station elevation angle	°	15	30	45
FSS earth station maximum gain	dBi	38.2	38.2	38.2
Polarization loss	dB	3	3	3
Feeder loss	dB	3	3	3
Receiver protection threshold	dBm/MHz	− 130.8	− 130.8	− 130.8
Isolation (3 km)	dB	10.7957	20.3524	25.2099
Isolation (10 km)	dB	− 2.256	7.7797	14.7523

Table 7 Deterministic calculation conclusion—rural

ATG out-of-band unwanted emission	dBm/MHz	− 25		
ATG antenna element gain	dBi	5		
Scenario		Rural		
FSS earth station elevation angle	°	15	30	45
FSS earth station maximum gain	dBi	35.7	35.7	35.7
Polarization loss	dB	3	3	3
Feeder loss	dB	3	3	3
Receiver protection threshold	dBm/MHz	− 130.8	− 130.8	− 130.8
Isolation (3 km)	dB	8.29567	17.8524	22.7099
Isolation (10 km)	dB	− 4.75635	5.27974	12.2523

In the urban scene, when the flight altitude of the ATG system aircraft is 3 km, the coexistence of the two systems requires an additional isolation of 10.8–25.2 dB. When the ATG system aircraft is flying at an altitude of 10 km, an additional isolation of 7.78–14.75 dB is required to prevent interference. In rural scenarios, when the ATG system aircraft is flying at an altitude of 3 km, the two systems need to be isolated by an additional 8.3–22.7 dB to prevent interference. When the ATG system aircraft is flying at a height of 10 km, an additional isolation of 5.28–12.25 dB is required to prevent interference.

It can be concluded that in the same scenario, as the flight altitude of the ATG system increases, the additional isolation required for the coexistence of the ATG system and the FSS system is effectively reduced. At the same flight altitude, the additional isolation required for the coexistence of ATG systems and FSS systems is reduced when ATG aircraft fly from urban to rural areas. Therefore, in rural scenarios with higher flight altitudes, it will be easier for the two systems to coexist.

5 AI-based interference cancellation method

5.1 Prediction method of time series based on AI

Transformers were proposed by Vaswani et al. [21] as an architecture to efficiently model sequences. Each transformer block consists of a multi-head self-attention (MHSA) layer and a feed-forward multilayer perceptron (MLP), as shown in Fig. 6. The MHSA generates a trainable associate memory with a query (Q) and a pair of key (K)-value (V) pairs to an output via linearly transforming the input. Mathematically, the output of a MHSA is calculated by:

$$\text{Attention}\,(Q, K, V) = \text{softmax}\left(QK^{\mathrm{T}}/\sqrt{d}\right)V \tag{11}$$

where $\sqrt{d}$ is a scaling factor based on the depth of the network. The output of the MHSA is then normalized and fed into the MLP to generate the input to the next block. In the above self-attention, Q and K are multiplied to generate the attention map, which represents the correlation between all the tokens within each layer. It is used to retrieve

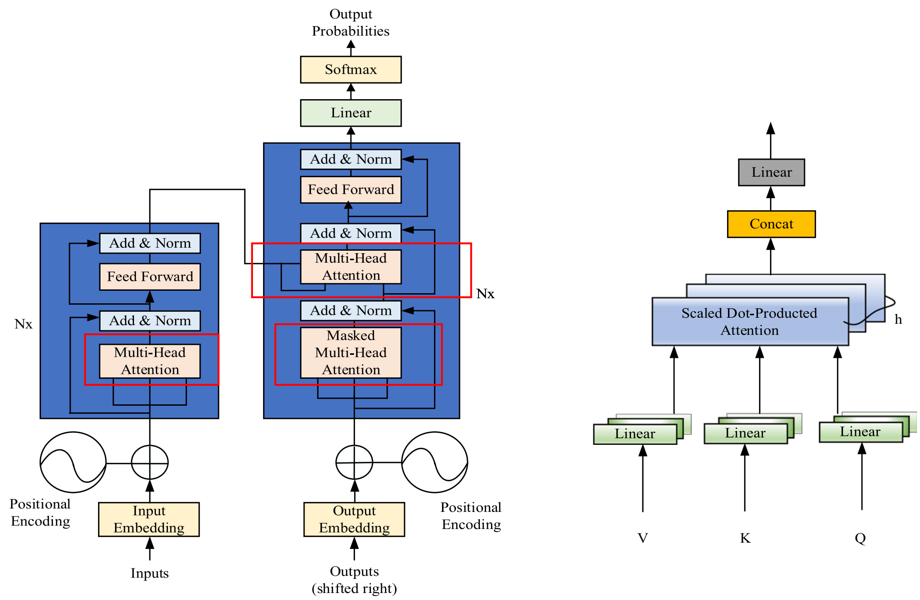

Fig. 6 Transformers architecture to efficiently model sequences

and combine the embeddings in the value V. This allows the layer to assign "credit" by implicitly forming state–return associations via similarity of the query and key vectors.

5.2 Power control method

The airborne ATG CPE power control algorithm based on AI prediction is used to eliminate interference to the 5G network. The airborne ATG CPE monitors the received ground 5G BS reference signal and records the reference signal receiving power RSRP. Assume that the airborne ATG CPE can monitor and record N RSRP values of the largest BS

$$\mathbf{I} = [\mathbf{I}_1, \mathbf{I}_2, \ldots, \mathbf{I}_\mathbf{N}] \tag{12}$$

where $\mathbf{I}_n$ represents the RSRP time series of the 5G base station received and recorded by the ATG CPE.

Time series is

$$\mathbf{I}_n = \left[I^n_{T-L}, \ldots, I^n_{T-1}, I^n_T\right] \tag{13}$$

where T is the current time and L is the length of time series. When the 5G BS RSRP power P_{BS} and the power on the same time–frequency unit of the ATG CPE are known, the estimated interference of the ATG CPE to the 5G BS is

$$\hat{I}^n_{T-l} = I^n_{T-l} - P_{\text{BS}} + P_{\text{CPE}} \tag{14}$$

Then we can know

$$\hat{\boldsymbol{I}}_{\boldsymbol{n}} = \left[\hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T-L}}, \ldots, \hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T-1}}, \hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T}}\right] \tag{15}$$

$$\hat{\boldsymbol{I}} = \left[\hat{\boldsymbol{I}}_1, \hat{\boldsymbol{I}}_2, \ldots, \hat{\boldsymbol{I}}_N\right], \tag{16}$$

Using AI model to predict time series

$$\hat{\boldsymbol{I}}_{\boldsymbol{n}} = \left[\hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T-L}}, \ldots, \hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T-1}}, \hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T}}\right] \tag{17}$$

seeing process 1 for training process of AI model, input

$$\hat{\boldsymbol{I}}'_{\boldsymbol{n}} = \left[\hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T-L}}, \ldots, \hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T-1}}, \hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T}}\right], \tag{18}$$

and output

$$\hat{\boldsymbol{I}}''_{\mathbf{n}} = \left[\hat{I}^n_{T+1}, \ldots, \hat{I}^n_{T+M}.\right] \tag{19}$$

Setting the tolerance limit of 5G BS for interference on each time–frequency resource as I_{MAX}, the combination vector is

$$\hat{\boldsymbol{I}}' = \left[\hat{\boldsymbol{I}}'_1, \hat{\boldsymbol{I}}'_2, \ldots, \hat{\boldsymbol{I}}'_{\mathbf{N}}\right] = \left[\hat{\boldsymbol{I}}^1_{\boldsymbol{T+1}}, \ldots, \hat{\boldsymbol{I}}^1_{\boldsymbol{T+M}}, \ldots, \hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T+1}}, \ldots, \hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T+M}}, \ldots, \hat{\boldsymbol{I}}^{\boldsymbol{N}}_{\boldsymbol{T+1}}, \ldots, \hat{\boldsymbol{I}}^{\boldsymbol{N}}_{\boldsymbol{T+M}}\right]. \tag{20}$$

It can be seen from the above that the transmission power control bias of the ATG CPE can be set to

$$\boldsymbol{P_{CPE\_offset}} = \boldsymbol{MAX}\left\{\left[\hat{\boldsymbol{I}}^1_{\boldsymbol{T+1}}, \ldots, \hat{\boldsymbol{I}}^1_{\boldsymbol{T+M}}, \ldots, \hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T+1}}, \ldots, \hat{\boldsymbol{I}}^{\boldsymbol{n}}_{\boldsymbol{T+M}}, \ldots, \hat{\boldsymbol{I}}^{\boldsymbol{N}}_{\boldsymbol{T+1}}, \ldots, \hat{\boldsymbol{I}}^{\boldsymbol{N}}_{\boldsymbol{T+M}}\right] - \boldsymbol{I_{max}}\right\} \tag{21}$$

When $P_{\text{CPE\_offset}} \leq 0$, interference elimination power control is not required. When $P_{\text{CPE\_offset}} > 0$, it is necessary to power control the transmission power

$$P'_{\text{CPE}} = P_{\text{CPE}} - P_{\text{CPE\_offset}} \tag{22}$$

The selection of the prediction length M, for a larger value M, will more effectively protect the 5G BS from interference. However, with the increase in M the prediction accuracy decreases, it will cause unnecessary power bigotry of the ATG CPE and degrade the uplink performance of the ATG network. For smaller value M, the decision-making time of ATG CPE will be shortened, and the potential interference risk to 5G BS will increase. Therefore, an appropriate value will also affect the performance of the algorithm.

5.3 Training process of AI model

Training Process 1: The Power Control Training Process of ATG CPE Based on AI

Input: Iterations E, A neural network consist of Encoder and Decoder, Datasets $\hat{\mathbf{I}}_{\mathrm{n}}^{'} = [\hat{I}_{T-L}^{n}, \cdots, \hat{I}_{T-1}^{n}, \hat{I}_{T}^{n}]$,$\hat{\mathbf{I}}_{\mathrm{n}}^{''} = [\hat{I}_{T+1}^{n}, \cdots, \hat{I}_{T+M}^{n}]$.

Output: Neural network parameters θ

Initialize $\theta \leftarrow \theta_0$,Embedding vector $X = Embedfunc(\hat{\mathbf{I}}_{\mathrm{n}}^{'})$,$X' = Embedfunc(\hat{\mathbf{I}}_{\mathrm{n}}^{''})$ which X and X' contain the interference estimation embedding and the sequence position embedding

for $epoch$ from 1 to E:

Encoder:

a) Calculate $(Q, K, V) = self\_attention(X)$

b) Output $z_1 = softmax\left(\frac{QK^T}{\sqrt{d_k}}\right)V$

c) $Add\ \&\ Norm$: $Z = Norm(MultiHeadAttention(X) + X)$, where MultiHead Attention means many times (n) in parallel compute Step a) and b) and then $Z = [z_1, \ldots, z_n]$

d) Encoder matrix $C = Add\ \&\ Norm\ , linear\ (Z)$

Decoder:

e) Calculate $(Q, K, V) = self\_attention(X')$

f) $MASK\ QK^T = QK^T \otimes MASK$

g) Output $z_1 = softmax\left(\frac{MASK\ QK^T}{\sqrt{d_k}}\right)V$

h) $Add\ \&\ Norm$:$Z = Norm(MultiHeadAttention(X') + X)$,where MultiHead Attention means many times (n) in parallel compute Step e) ,f) and g) and then $Z = [z_1, \ldots, z_n]$

i) Calculate $(Q, K, V) = self\_attention(C, Z)$

j) Output $z_1 = softmax\left(\frac{QK^T}{\sqrt{d_k}}\right)V$

k) $Add\ \&\ Norm$: $Z = Norm(MultiHeadAttention(C, Z) + C)$,where MultiHead Attention means many times (n) in parallel compute Step i) and j) and then $Z = [z_1, \ldots, z_n]$

l) Decoder matrix $O = Add\ \&\ Norm\ , linear\ (Z)$

m) Calculate loss $L = \sum \mathcal{L}(softmax(O), \hat{\mathbf{I}}_{\mathrm{n}}^{''})$

From Fig. 7, the results of numerical analysis, in extreme cases, ATG CPE will cause co-channel harmful interference to 5G base stations. In order to avoid harmful interference in such extreme cases, we design a power control method based on artificial intelligence timing sequence prediction. The ML-based prediction parameter configuration is shown in the table above. Based on the interference from the time series $T - L$ to T, the interference value from $T+1$ to $T+M$ is effectively predicted, and the pre-power is performed based on the interference prediction to avoid interference to the 5G base station.

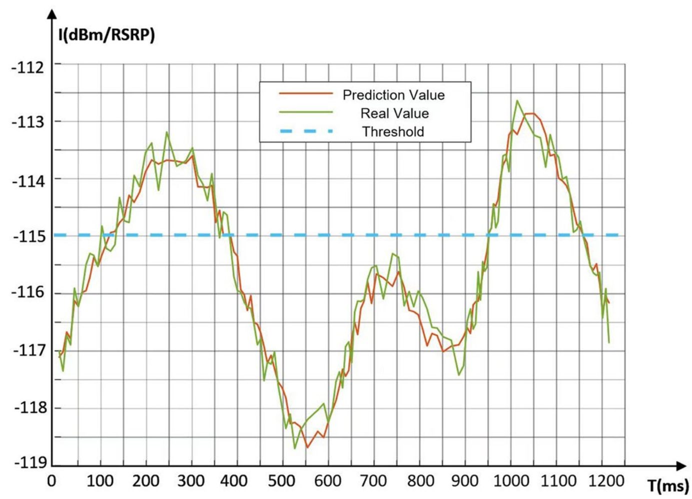

Fig. 7 Interference prediction

6 Conclusions

The employment of ATG BS and airborne CPE is seen as a promising solution to improve the performance of IoT cellular systems. According to the analysis in this paper, when the ATG airborne CPE uplink signal interferes with the base station of the 5G mobile communication system on the same frequency, the coexistence between systems requires an additional isolation of 0.05–20 dB. As the flight altitude increases, the isolation required for the coexistence of the two systems decreases. When the aircraft flies over the city, the point with the strongest interference between the ATG system and the 5G system is closer to the disturbed base station. When the ATG airborne CPE uplink signal interferes with the adjacent frequency satellite earth station, the two systems need an additional isolation of 5.28–25.2 dB to achieve coexistence between the systems. As the ATG flight altitude increases, and in rural scenarios, the additional isolation required for the coexistence of the ATG system and the FSS system is effectively reduced. It can be seen that due to the stricter protection requirements of the FSS system, the interference of ATG airborne equipment on the same frequency 5G system is lower than that of adjacent frequency FSS system. However, through comparison, it can be found that the higher the flight altitude of the aircraft, the smaller the impact of the ATG system on other systems.

To solve the problem above, some interference mitigation approaches can be considered to realize the coexistence of 3.5 GHz ATG system and other systems at the same frequency and adjacent frequencies. Possible solutions include appropriate power control of the on-board CPE of the ATG system or tightening of the out-of-band rejection indicator.

Abbreviations

IoT	Internet of things
UAV	Unmanned aerial vehicle
FSS	Fixed satellite service
3 D	Three-dimensional
ATG	Air to ground
BS	Base station
OOB	Out of band

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In this paper, LL conceived, designed and wrote the study. All authors read, revised and approved the manuscript.

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The data are internal company data, involve trade secrets and cannot be shared.

Declarations

Competing interests
The authors declare that they have no competing interests.

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References

1. H. Tran-Dang, N. Krommenacker, P. Charpentier, D.-S. Kim, Toward the Internet of Things for physical internet: perspectives and challenges. IEEE Internet Things J. **7**(6), 4711–4736 (2020). https://doi.org/10.1109/JIOT.2020.2971736
2. L. Liu, S. Zhang, R. Zhang, Multi-beam UAV communication in cellular uplink: cooperative interference cancellation and sum-rate maximization. IEEE Trans. Wirel. Commun. **18**(10), 4679–4691 (2019). https://doi.org/10.1109/TWC.2019.2926981
3. L. You, K.-X. Li, J. Wang, X. Gao, X.-G. Xia, B. Ottersten, Massive MIMO transmission for LEO satellite communications. IEEE J. Sel. Areas Commun. **38**(8), 1851–1865 (2020). https://doi.org/10.1109/JSAC.2020.3000803
4. Y. Cheng, W. Huang, Y. Liu, X. Pei, Z. Zhou, K. Zhu, Complexity-reduced single sideband and narrowband doppler spectrum filtering method for ATG fading channel simulation, in *2020 IEEE 2nd International Conference on Civil Aviation Safety and Information Technology (ICCASIT*), pp. 944–949 (2020). https://doi.org/10.1109/ICCASIT50869.2020.9368804
5. S. Wang et al., A novel method view to estimate 5G spectrum needs for land mobile service, in *2016 16th International Symposium on Communications and Information Technologies (ISCIT)*, pp. 402–406 (2016). https://doi.org/10.1109/ISCIT.2016.7751660
6. H. Yang, Application and development of mobile communication technology, in *2021 International Wireless Communications and Mobile Computing (IWCMC)*, pp. 893–896 (2021). https://doi.org/10.1109/IWCMC51323.2021.9498908
7. C. Morlet, F. Ongaro, N. Ricard, A. Santovincenzo, ESA Iris Programme: Design options for the satellite communication sub-network of the European Air Traffic Management System, in *29th Digital Avionics Systems Conference*, pp. 3.C.1–1–3.C.1–13 (2010). https://doi.org/10.1109/DASC.2010.5655375
8. G.R. Schloemer, Air to ground communications system and method (1991)
9. G. Chen, Z. Ren, Y. Li, T. Zhang, A method of same frequency interference elimination based on adaptive notch filter. Int. Workshop Intell. Syst. Appl. **2009**, 1–4 (2009). https://doi.org/10.1109/IWISA.2009.5072637.\
10. E. Dine, M. Vondra, S. Hofmann et al., In-flight broadband connectivity: architectures and business models for high capacity air-to-ground communications. IEEE Commun. Mag. **55**(9), 142–149 (2017)
11. H. Tang, X. Zong, B. Chen, Z. Nie, Antenna array configuration in air-to-ground communications scenario, in *2018 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC)*, pp. 1–3 (2018)
12. Recommendation ITU-R M.2101–0, Modeling and simulation of IMT networks and systems for use in sharing and compatibility studies[R]. 2017.02
13. ITU-R Report S.2199–0, Studies on compatibility of broadband wireless access (BWA) systems and fixed-satellite service (FSS) networks in the 3 400–4 200 MHz band[R].2010
14. ITU-R Recommendation S.1432–1, Apportionment of the allowable error performance degradations to fixed-satellite service (FSS) hypothetical reference digital paths arising from time invariant interference for systems operating below 30 GHz[R]. 2006. 04
15. ITU-R Recommendation P.525–4, Calculation of free-space attenuation[R]. 2019.08
16. ITU-R Recommendation P.2108–1, Prediction of clutter loss [R]. 2021.09
17. ITU-R Document 5D/716-E, "Characteristics of terrestrial component of IMT for sharing and compatibility studies in preparation for WRC-23," in Geneva, 2021
18. ITU-R Recommendation S.465–6. Reference radiation pattern of earth station antennas in the fixed-satellite service for use in coordination and interference assessment in the frequency range from 2 to 31 GHz [R].2010.01
19. B. Smida, V. Tarokh, Analysis of interference in air-to-ground CDMA cellular systems under idealized assumptions. IEEE Trans. Commun. **59**(1), 258–267 (2011)
20. B. Smida, V. Tarokh, Ground-to-air interference analysis in cellular ATG systems, in *2008 42nd Annual Conference on Information Sciences and Systems*, pp. 225–228 (2008). https://doi.org/10.1109/CISS.2008.4558525
21. A.V. Aswani, N. Shazeer, N. Parmar, J. Uszkoreit, L. Jones, A.N. Gomez, L. Kaiser, I. Polosukhin. Attention is all you need. In Advances in Neural Information Processing Systems (2017)

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