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Wireless Link Modeling Method Based on Directional Communication of Flying Ad Hoc Networks

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Abstract: With the increasing applications of unmanned aerial vehicles (UAVs) in communications, surveillance, and emergency response, Flying Ad Hoc Networks (FANETs) have emerged as a flexible and efficient network architecture. However, the high mobility of nodes, dynamic topology changes and directional communication in FANETs pose significant challenges to wireless link modeling. We are addressing the limitations of traditional models in fully capturing the channel characteristics of directional antennas and three-dimensional dynamic environments. This paper proposes a wireless link modeling method based on directional communication of FANETs. The proposed method integrates 3D spatial topology computation and dynamic interference environment simulation to rigorously characterize link properties influenced by directional antenna gain, node mobility, and external interference. By leveraging MATLAB-generated bit error rate (BER) lookup tables, this framework enables efficient wireless link evaluation in simulated flight scenarios. Experimental results demonstrate that compared to traditional statistical models, our approach achieves comprehensive, scenario-based link performance evaluation, providing critical support for FANET optimization and performance enhancement.

1. Introduction

In recent years, the rapid development of UAV technology has promoted the wide application of FANETs in fields such as communication relay, battlefield reconnaissance, and disaster monitoring[1]. Unlike traditional Mobile Ad Hoc Networks (MANETs) and Vehicular Ad Hoc Networks (VANETs), FANETs exhibit unique 3D mobility, high dynamics, and node sparsity, making wireless link modeling a critical task[2]. The introduction of directional antenna technology enables higher gain and interference resistance in specific directions, thereby enhancing network coverage and data transmission efficiency. However, directional communication introduces new complexities, such as beam alignment in three-dimensional space, dynamic changes in directional antenna gain, Doppler frequency shifts due to high node mobility, and electromagnetic interference. These factors render traditional wireless link models inadequate for accurately characterizing FANETs' channel characteristics.

Existing research has made some progress in wireless link modeling. Statistical models, due to their simplicity, have been widely used in the early analysis of wireless networks. However, their assumption of a uniform environment contradicts the dynamic three-dimensional scenario of FANETs, leading to insufficient accuracy[3]. Geometry-based ray-tracing methods can provide higher resolution, but they have high computational complexity and are difficult to adapt to the real-time requirements of rapidly moving nodes and changing environments[4]. Moreover, channel prediction methods based on machine learning have garnered attention in recent years. However, they rely heavily on large amounts of labeled data and have limited generalization capabilities in sparse node scenarios[5]. To address the aforementioned issues, there is an urgent need for a wireless link modeling method that can finely characterize the directional communication features of FANETs, in order to support network protocol design, resource allocation, and performance optimization.

This paper proposes a wireless link modeling method based on directional communication of FANETs. The method integrates techniques such as three-dimensional spatial topology calculation and dynamic interference environment simulation. It fully considers the directivity gain of directional antennas, the spatial distribution of communication nodes, and the dynamic impacts of node mobility and interference. This approach constructs a high-precision channel model suitable for FANETs.

2. Design Philosophy

The wireless link modeling for directional communication in FANETs is used to achieve the performance of data links between aircraft in complex electromagnetic environments. This includes the modeling of communication signals, interference signals, and noise signals, as well as the analysis of link performance. Initially, an offline signal-level simulation and computation approach is adopted. Using MATLAB, the BER is simulated under different communication rates, encoding parameters, modulation parameters, and signal-to-noise ratio (SNR), and a BER lookup table is established. During online simulation, the BER lookup table data is loaded. First, through functional-level simulation and computation, the power of directional communication, noise, and interference signals in dynamic scenarios is obtained to derive the SNR parameters. Then, based on these SNR parameters, combined with communication rate levels, channel encoding parameters, and modulation parameters, the BER for communication links is obtained from the lookup table. Finally, the packet error rate (PER) is calculated based on the BER and frame length.

3. Model Construction Method

3.1. Topology Calculation

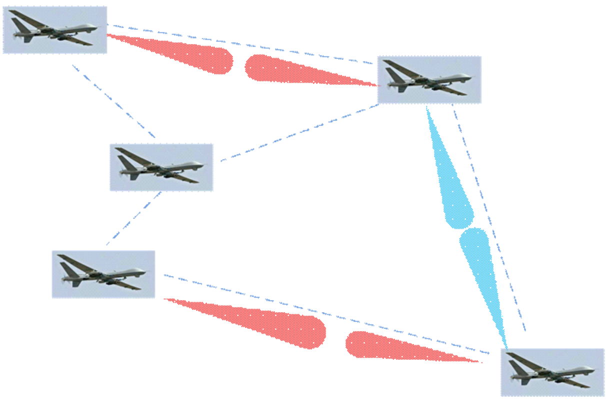

Figure 1: Topology Calculation Model

The topology calculation is a fundamental step in our link calculation model.The topology structure of the FANET is shown in Figure 1. It involves determining the three-dimensional positions of all communication nodes within the FANET, considering factors such as node mobility, altitude, and flight trajectory. By accurately modeling the spatial distribution of nodes, we can better understand the potential for communication links, which is crucial for predicting link performance. Additionally, the topology calculation helps in identifying potential bottlenecks or areas of high interference, enabling more effective resource allocation and network optimization strategies.

3.2. Link Calculation

Based on typical mission requirements and scenarios[6], the default channel model is assumed to be an Additive White Gaussian Noise (AWGN) channel. The BER and PER of the inter-device communication links are calculated for different SNRs.The composition of the link calculation model is shown in Figure 2.

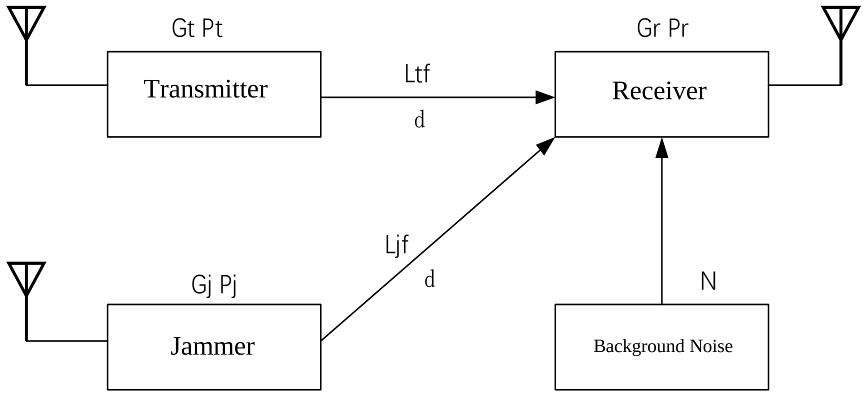

Figure 2: Link Calculation Model

Estimation Methods for Each Part of the Link Model:

(1)Link Loss Calculation

(a) Path Loss

$$L_{tf} = (\frac{4\pi d}{\lambda})^2$$

λ is the wavelength of the signal; d is the transmission distance.

The path loss expressed in dB is

$$L_{tf} = 32.4 + 20logf(MHZ) + 20logd(km)$$

(b) Atmospheric Attenuation

Considering the refraction and absorption of radio waves by the troposphere, as well as the refraction and attenuation caused by atmospheric conditions such as clouds, rain, fog, snow, and dust, the atmospheric attenuation model includes the tropospheric refraction loss model, the tropospheric absorption loss model, and the attenuation models for clouds, rain, fog, snow, and dust. The tropospheric refraction loss model calculates the loss due to the atmospheric lensing effect. To improve computational efficiency, a fifth-order polynomial fitting formula is generally used.

$$L_{len} = c_5 * rcal^5 + c_4 * rcal^4 + c_3 * rcal^3 + c_2 * rcal^2 + c_1 * rcal + c_0 \ (dB)$$

where rcal=lg(R), R is the slant range, 30nmile≤R≤3000 nmile(in nautical miles)

(c) Polarization attenuation

The polarization loss is estimated based on the polarization of the transmitting and receiving antennas. When a 45 °polarized antenna is used to receive vertically or horizontally polarized waves, or when a vertically or horizontally polarized antenna is used to receive 45 °polarized waves, or when a circularly polarized antenna is used to receive any linearly polarized waves, or when a linearly polarized antenna is used to receive any circularly polarized waves, the polarization loss is -3 dB. When the polarization direction of the receiving antenna is completely orthogonal to the polarization direction of the incoming wave, polarization isolation occurs, and the incoming wave energy cannot be received.

(2)Calculation of Signal Reception Power at the Aperture of the Receiving Antenna

$$P_{r(dBm)} = P_{t(dBm)} + G_{t(dB)}(\theta) + G_{r(dB)}(\theta') - L_{(dB)}$$

P_t is the transmit power, $G_t(\theta), G_r(\theta')$is the directional gain of the transmitting and receiving antenna, L is the link Loss, which includes path loss, atmospheric attenuation, and polarization attenuation.

During the simulation, the received signal power is compared with the receiver sensitivity. If the power is less than the sensitivity, the link is directly determined to be unavailable, and no further analysis of the BER or frame error rate (FER) is performed.

(3)Calculation of Interference Power at the Receiving Antenna Aperture

$$P_{j(dBm)} = P_{jt(dBm)} + G_{jt(dB)}(\theta) + G_{r(dB)}(\theta') - L_{j(dB)} - 10lg\frac{B_r}{B_j}$$

P_{jt} is the transmit power of the interferer, G_{jt} is the directional gain of the interferer's antenna in the transmission direction, and L_j is the path loss, atmospheric attenuation, and polarization loss from the interferer to the receiver. If multiple interferers are jamming the same communication equipment, the interference power at the receiving antenna aperture of the communication equipment is the superposition of the interference power from multiple sources.

(4)Calculation of In-band Background Noise at the Receiver

$$N_{dBm} = N_{T_0}(dBm) + 10log10(B_n) + F_n(dB)$$

$$N_{T_0}(dBm) = KT_0 = 1.38 \times 10^{-23} \times 290 \approx -174\text{dBm/Hz}$$

K=1.381 $\times 10^{-23}$J/K, T=290K,$\mathrm{B_n}$ is the equivalent noise bandwidth of the receiver, and $\mathrm{F_n}$ is the noise figure.

(5)SNR at the Receiver Input

$$\text{S/N}=10\log10(\frac{P_{r(mw)}}{P_{j(mw)+N_{(mw)}}})$$

3.3. Calculation of BER and FER

3.3.1. BER

During the data transmission process, operations such as CRC checking, scrambling, channel coding, interleaving, and modulation, as well as the corresponding data reception process, are simulated using an offline signal-level simulation approach. MATLAB is employed to simulate the BER under various communication rates, coding parameters, modulation parameters, and SNRs. A BER lookup table is then established and loaded during online simulation. For the gain improvement provided by spread-spectrum technology, a reasonable additional gain can be set after considering factors such as the length of the spreading code and the spreading code rate.

Therefore, the input parameters for the offline calculation of link BER are as follows:

- Data rate: Information rate;

- Data length: Waveform frame length, data length;
- Channel coding parameters: Code rate, number of repetition encoding times;
- Channel interleaving parameters: Block interleaving depth, number of rows and columns for code block interleaving;
- Modulation parameters: Gaussian low-pass filter BTb value, with a default BTb = 0.3;
- SNR.

The simulation parameters and results using MATLAB are illustrated as Figure 3:

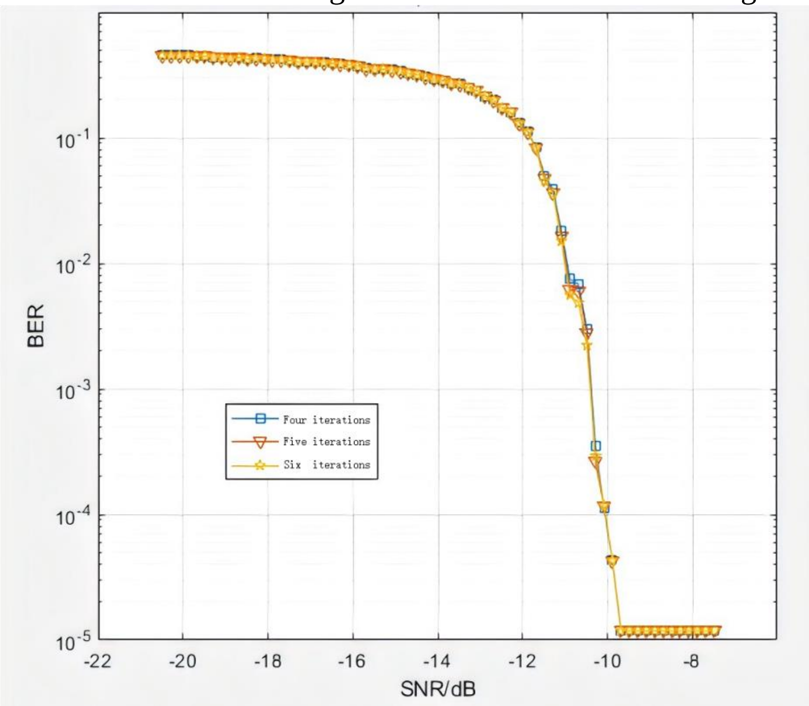

Figure 3: SNR/BER Curve Diagram

3.3.2. FER

Assuming the BER follows a binomial distribution, the relationship between the P_F and P_e BER can be expressed as:

$$P_F = 1 - (1 - P_e)^N$$

where N is the number of bits in a frame.

3.4. Execution Process

The calculation process of the link calculation model is shown in the figure below.
The calculation process is as Figure 4:

a) First, obtain the parameters of the aircraft transmitter, receiver, and antenna, as well as the initial data of the positions and attitudes of each aircraft. Calculate the spatial relative angles and relative distances between the transmitting and receiving antennas of each aircraft based on the topological relationships.
b) Obtain the parameters of the jamming reconnaissance equipment and the motion parameters of the jammer. Calculate the interference signal characteristics at the receiving aperture of the communication equipment.
c) Based on the aircraft motion parameters, transmission power, directional gain of the transmitting and receiving antennas, and link loss, calculate the signal reception power at the

receiving antenna aperture of the communication equipment.

d) Based on the signal reception power at the receiving antenna aperture, the interference power at the receiving antenna aperture, the in-band background noise of the receiver, the set spreading gain, and the calculated frequency-hopping gain, calculate the SNR at the input end of the communication equipment receiver.

e) Based on the SNR at the input end of the communication equipment receiver, and in combination with the communication rate, query the offline stored BER file to output the BER between each aircraft. Calculate the FER based on the BER and frame length.

f) If the simulation has not ended, proceed to the next simulation time step, obtain the position and attitude data of each aircraft and the motion data of the jammer at that time step, and repeat the calculations until the simulation ends.

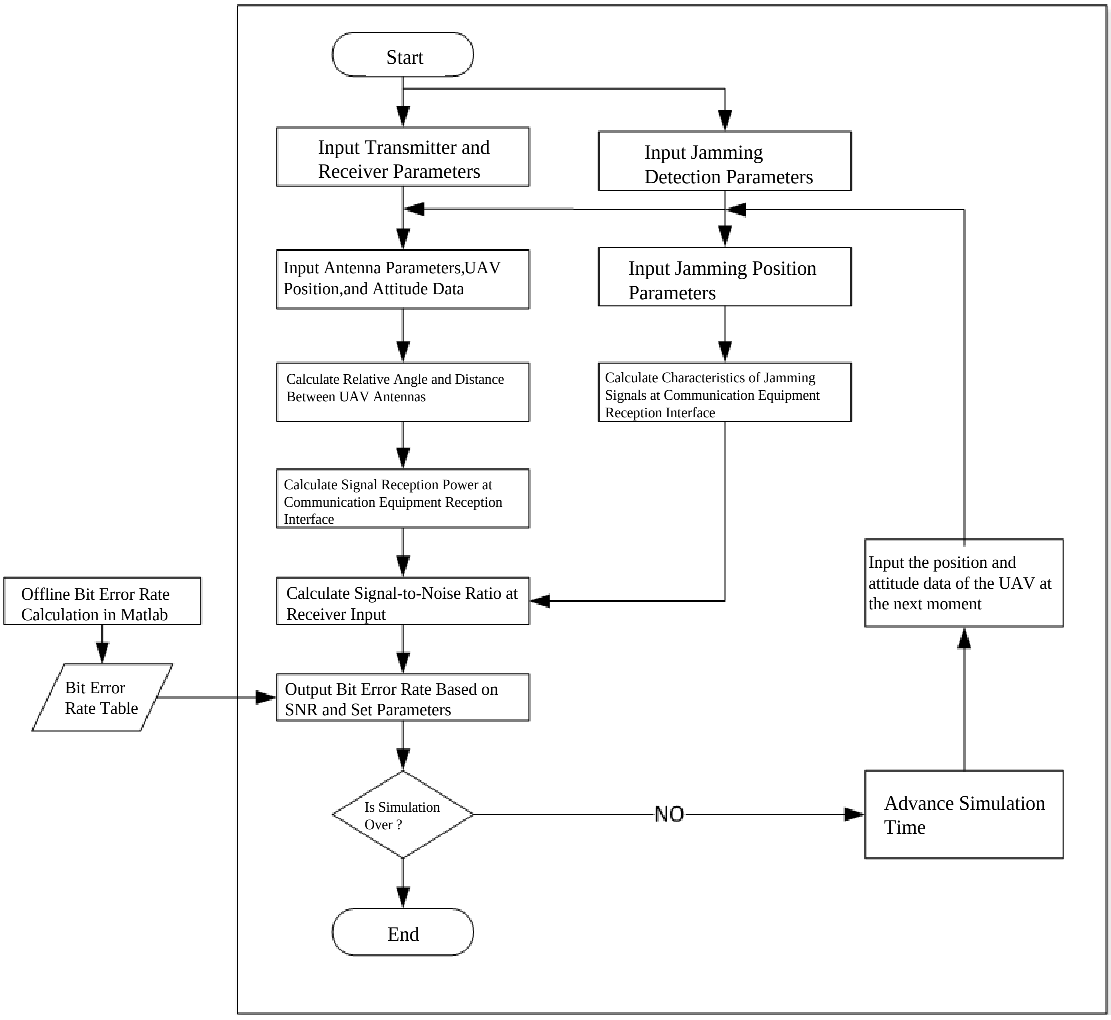

Figure 4: Link Calculation Process

4. Summary

This paper addresses the need for wireless link modeling in directional communications within FANETs by proposing a novel high-precision modeling method to overcome the limitations of traditional models in complex three-dimensional dynamic environments. The high mobility, dynamic topology changes, and the introduction of directional antennas in FANETs make it difficult for traditional statistical and geometric models to fully characterize the channel properties. To this end, this study combines three-dimensional spatial topology calculations and dynamic interference environment simulations to construct a refined wireless link model, which comprehensively considers the directivity gain of directional antennas, node mobility, and the impact of external electromagnetic interference. Through a two-stage strategy of offline signal-level simulation and online functional-level simulation, the method first uses MATLAB to generate BER lookup tables for different communication parameters. Subsequently, it performs real-time link performance evaluation in dynamic flight scenarios through SNR calculations and table lookups. Experimental results demonstrate that, compared to traditional statistical models, the proposed method shows significant advantages in predicting BER and FER, enabling full-process link performance evaluation and verification for specific flight scenarios. This improvement is attributed to the model's refined description of directional communication characteristics and effective simulation of dynamic interference environments, providing important theoretical support and practical guidance for the optimization design, protocol development, and resource allocation of FANETs. Moreover, by dividing the simulation process into offline and online stages, the method reduces the complexity of real-time calculations while maintaining high precision, showing strong potential for engineering applications.

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