A Multiple Access Method For Integrated Sensing and Communication Enabled UAV Ad Hoc Network

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***Abstract*—In this paper, a novel multiple access method is proposed and evaluated for integrated sensing and communication (ISAC) enabled UAV ad hoc network, in which the UAVs can perform sensing and communicating simultaneously. With integrated signal, a novel spatial division method is proposed based on a multi-beam framework with tunable analog antenna arrays for ISAC system. With the implementation of such spatial division method, we design a new time-frequency resource allocation scheme by dividing the integrated signal into Radar (R) mode and Radar Communication (RC) mode. Moreover, according to the packet arrival rate, to make full use of spectrum resources, a novel procedure to assign channels is proposed. The performance of medium access method is analyzed by using Markov model. Simulation results shows that the multiple access method proposed in this paper has improved the throughput of UAV nodes with the assistance of sensing information.**

***Index Terms*—Integrated sensing and communication, space allocation, spectrum and time slot allocation, cooperative sensing, MAC protocol.**

I. Introduction

Nowadays, unmanned aerial vehicle (UAV) technology is becoming more and more mature [1], which has been widely used in various daily life scenarios such as aerial photography, express transportation and disaster monitoring. Due to the shortcomings of single UAV in sensing range and accuracy, ad hoc networking by multiple UAVs is becoming an important research trend. The UAV network can collaborate more efficiently and economically to accomplish more tasks [2] and have the advantages of safety and reliability [3], system stability, and wide coverage.

The integrated sensing and communication (ISAC) technology has the advantage of sharing hardware and spectrum resources, and has certain advantages in reducing cost and size. Therefore, the application of ISAC technology to UAV has gradually become a research hotspot. Z. Feng $et\ al.$ discussed the application of the ISAC system in UAV networks [4]. Based on the integration of radar communication in [5], L. Huang $et\ al.$ proposed a phased array radar space channel model and channel estimation scheme, which can be applied in the UAV network. B. Paul $et\ al.$ discussed the design of radar communication coexistence system in [6], and foresee the huge development space in this field in the future.

Regarding the multi-access control protocol of the UAV network, many schemes have been discussed. For instance, [7] proposed the space division multiple access (SDMA) protocol for the UAV network to increase capacity. For the situation where the data flow is highly asymmetric in the uplink and downlink, Gu et al. proposed the centralized intelligent channel assigned multiple access (C-ICAMA) protocol in [8] to reduce the access delay. [9] proposed a multiple access protocol for the UAV network for full-duplex transmission to reduce communication delay.

Although many papers have investigated the multi-access protocols for UAV networks, there are few studies concentrated on multi-access protocols for UAV networks in ISAC scenarios. Ma $et\ al.$ proposed a ISAC multiple access method for vehicular networks in [10]. But it does not address the problem of exposed terminals and has a large access conflict problem when the number of nodes is large. Therefore, in this paper, we will propose a novel multiple access method in domains of time, frequency and space for UAV ad hoc ISAC systems, which can use the sensing information to improve the efficiency of access, and realize the communication while ensuring the full-time detection of the radar.

The rest part of this paper is organized as follows. In Section II the system model is introduced, including the usage of Radar (R) mode for radar detection and Radar Communication (RC) mode for the ISAC system, and a UAV ad hoc multiple access method is proposed. In Section III, the Markov model is used to analyze the throughput performance of the MAC protocol. In Section IV, the simulation results are provided, which verifies the analysis in the previous chapters. Finally, we summarize this paper in Section V.

II. System Model

It is assumed that the information transmission and environment sensing in the UAV network is completed by using ISAC signals. Although ISAC signals can perform both radar detection and communication transmission, the mixed modulation of the signal may have certain impacts on communication and radar performance. Therefore, we divide the signal into R mode and RC mode according to the communication requirements.

In the R mode, the ISAC system is simplified to a traditional radar system. The R mode is used for periodic radar detection and the UAV can not interact with other users. In the RC mode,

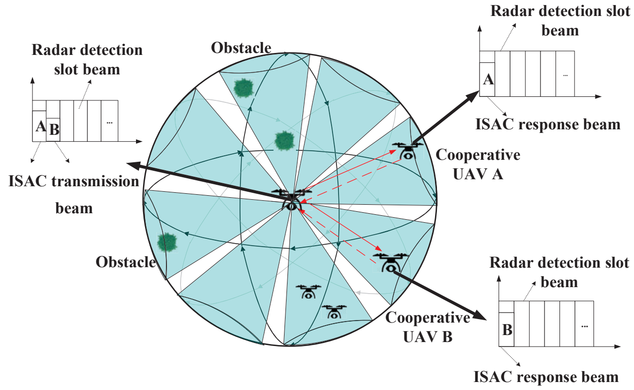

Fig. 1: System model

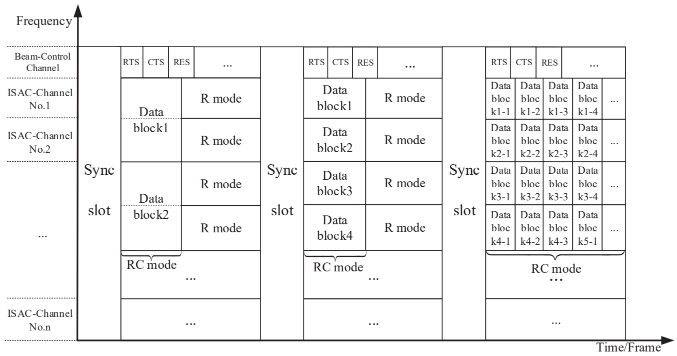

Fig. 2: Channel multiplexing method

UAV can communicate with users and detect radar targets simultaneously by ISAC signals. When the system works in the RC mode, the communication module transmits data while the radar achieves target detection. In the ISAC system, the MAC protocol will be utilized to switch between R mode and RC mode, thereby scheduling the radar and communication functionalities. The following section will introduce the allocation of both spatial and time-frequency resources.

A. Spatial Division

To make better use of spatial resources, a novel multibeam framework using steerable analog antenna arrays is proposed in [11], since the framework provides fixed subbeam for communication and packet-varying scanning subbeam for sensing. Fig.1 shows the system structure, a multiple access method for the ISAC system is proposed, where the UAV is able to accomplish full-time detection in order to obtain timely information of the surrounding environment, the short frame data sent by the UAV uses the radar signal as the carrier, and the communication signal is added on top of it. When there are communication requirements, the detection UAV interacts with the cooperative UAVs.

B. Time-Frequency Division

Although the UAV network utilize spatial division, there still might be more UAVs in a single beam coverage direction in some dense cases. Therefore, the UAV should further allocate resources in the time and frequency domain beyond spatial domain during the directional transmission process to ensure the demand for efficient data transmission.

The proposed multiple access method adopts some mechanisms in IEEE 802.11 Distributed Collaboration Function (DCF) such as Carrier Sense Multiple Access with Collision Avoid (CSMA/CA), Request To Send/Clear To Send (RTS/CTS) handshake mechanism, Binary Exponential Backoff (BEB) and Interframe Space. Moreover, for the multi-channel model, the cooperative UAV send a Reservation (RES) control packet which prohibits its neighbors from using the same channel. As shown in Fig.2, we divide the frequency resource into beam control channel and ISAC channels and use three short frame periods to show three typical situations.

In the first case, the number of UAV nodes is low, which can support a single UAV node to occupy multiple ISAC channels. The physical layer using Orthogonal Frequency Division Multiplexing (OFDM) signals in the 802.11n protocol can already support multi-channel integration [12]. Therefore, a single UAV node transmits through multiple ISAC channels in RC mode, further increase the throughput of UAV nodes. After all transmissions are completed, the channel will switch to R mode. In the second case, when the number of UAVs within a single beam is close to the number of ISAC channels, each UAV node will be assigned to a single ISAC channel in RC mode. After the information transmission is completed, the system will switch to R mode to conduct periodic sensing and detection for the remaining time. In the third case, when the overall data exceeds the system capacity, each UAV packet will be divided into multiple packets and will be sent independently through multiple channels.

III. THEORETICAL ANALYSIS

A. Markov Chain Model

We assume that adjacent UAV nodes are evenly distributed around the central UAV. By analyzing the Markov model of the beam control channel, we can get the collision probability P_{co} and the transmission probability τ in the steady-state on the kth beam.

If there are packets to be transmitted in the UAV network, UAVs start sensing the beam control channel. When the channel is idle in DCF inter frame space time T_{DIFS}, UAVs send control information packets and wait a period to avoid interference with the integrated signal echoes. Otherwise, the UAV takes a random backoff to avoid collision.

Let $i(t)$ and $j(t)$ be the stochastic process which are backoff stage and backoff time counter for the UAV at time t, respectively where i and j denote the value of the backoff stage and backoff counter. If m and W_{c0} are the maximum backoff value and minimum contention window, then The first value of j is randomly selected from $[0, W_{c0} - 1]$. If the channel is sensed free for a slot time, j is decreased by 1, and the UAV will transmit the packet when j is 0. If a collision takes place after a transmission, then i is increased by 1. W_c doubles after each failed transmission and can have the maximum value

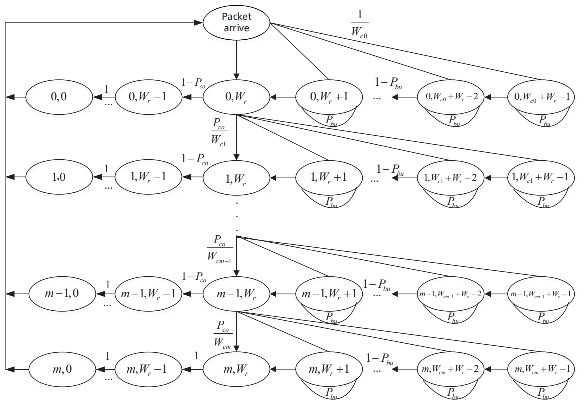

Fig. 3: Markov chain

$W_{cm} = 2^m W_{c0}$. To avoid echo interference of the integrated signal, we set a integrated signal echoes backoff window W_r, W_r is decreased by 1 for each time slot and the UAV will make the next send until W_r is reduced to 0, then the ISAC system backoff window W_i can be expressed as

$$W_i = 2^i W_{c0} + W_r, 0 \le i \le m. \tag{1}$$

The Fig.3 shows a two-dimensional process with a discrete-time Markov chain, where

$$\begin{cases} P[(i,j)|(i,j+1)] = 1 - P_{bu} & j \in (W_r - 1, W_i - 2) \\ P[(i,j)|(i,j+1)] = 1 & j \in (0, W_r - 2) \\ P[(i,W_r-1)|(i,W_r)] = 1 - P_{co} & \\ P[(m,W_r-1)|(m,W_r)] = 1 & \\ P[(i,j)|(i-1,W_r)] = P_{co}/W_{ci} & j \in (W_r, W_i - 1) \\ P[(0,j)|(i,0)] = 1/W_{c0} & j \in (W_r, W_0 - 1). \end{cases} \tag{2}$$

Let $b_{i,j} = \lim_{t\to\infty} P\{i(t) = i, j(t) = j\}, (i \in (0,m), j \in (0, W_i - 1))$ be the stationary distribution of the Markov chain. From the Markov chain, when $j \in (0, W_r - 1)$, the stationary distribution probabilities of states $\{i,j\}$ can be derived as

$$b_{i,j} = (1 - P_{co}) b_{i,W_r}, \tag{3}$$

where

$$b_{i,W_r} = \begin{cases} (1 - P_{co}) \sum_{j=0}^{m} b_{j,W_r} + b_{m,W_r}, i = 0 \\ \\ P_{co} \cdot b_{i-1,W_r}, 0 < i \le m \end{cases}, \tag{4}$$

and when $j \in (W_r, W_i - 1)$, the stationary distribution probabilities of states $\{i,j\}$ can be derived as

$$b_{i,j} = \frac{W_i - W_r - j}{(W_i - W_r)(1 - P_{bu})} b_{i,W_r}, \tag{5}$$

the total probability is one,

$$\begin{aligned} 1 &= \sum_{i=0}^{m} \sum_{j=0}^{W_i - 1} b_{i,k} = \sum_{i=0}^{m} \sum_{j=0}^{W_r - 1} b_{i,j} + \sum_{i=0}^{m} \sum_{j=W_r}^{W_i - 1} b_{i,j} \\ &= b_{0,W_r} \left(\sum_{i=0}^{m} (1 - P_{co}) W_r {P_{co}}^i + \sum_{i=0}^{m} \frac{W_i - W_r + 1}{2(1 - P_{bu})} {P_{co}}^i \right), \end{aligned} \tag{6}$$

the stationary probability distribution of state $\{0, W_r\}$ is

$$b_{0,W_r} = \frac{2(1 - P_{bu})(1 - 2P_{co})(1 - P_{co})}{X}, \tag{7}$$

where $X = [2W_r(1 - P_{bu})(1 - P_{co}) + 1] (1 - {P_{co}}^{m+1})(1 - 2P_{co}) + W_{c0} \left[1 - (2P_{co})^{m+1}\right] (1 - P_{co})$.

There are n UAV nodes in the kth beam, and in a random time slot t, each UAV node tries to send a packet with a stationary probability τ, and the transmission probability τ can be written as

$$\tau = \sum_{i=0}^{m} b_{i,W_r} = \frac{1 - {P_{co}}^{m+1}}{1 - P_{co}} b_{0,W_r}. \tag{8}$$

Assuming that the number of UAVs in the beam is n, so we can get the collision probability P_{co}, channel busy probability P_{bu} and the probability of successful transmission P_{su} as

$$P_{co} = 1 - (1 - \tau)^{n-1}, \tag{9}$$

$$P_{bu} = 1 - (1 - \tau)^{n}, \tag{10}$$

$$P_{su} = \frac{n\tau(1 - \tau)^{n-1}}{P_{bu}}. \tag{11}$$

B. Throughput analysis

Let S_c be the ISAC system throughput which is the mean data transferred over the average period of slot time on the beam control channel which can be expressed as

$$S_c = \frac{P_{bu} P_{su} E[P]}{P_{su}(T_s + 2T_{\Delta d}) + (1 - P_{bu}) T_\sigma + (P_{bu} - P_{su}) T_c}, \tag{12}$$

where T_σ represents the duration of the idle slot, T_s is the average time of successful transmission, $T_{\Delta d}$ is the average time to wait for the integrated signal echoes and T_c is the average time of channel busy, which can be written as follows:

$$T_s = T_{RTS} + T_{CTS} + T_{RES} + T_{DIFS} + 2T_{SIFS} + 2T_\sigma, \tag{13}$$

$$T_{\Delta d} = \frac{\sqrt{(x^i - x^j)^2 + (y^i - y^j)^2 + (z^i - z^j)^2}}{c_0}, \tag{14}$$

$$T_c = T_{RTS} + T_{EIFS}. \tag{15}$$

T_{RTS}, T_{CTS}, and T_{RES} are the transmission duration of the control packets RTS, CTS and RES, respectively. (x, y, z) is the position of the target relative to the UAV, T_{SIFS}, T_{DIFS} are the lengths of SIFS and DIFS frames. T_{EIFS} is the duration of waiting for retransmission when a conflict occurs.

In the ISAC system, the UAV network can use the sensing information to optimize the communication backoff window W_0, so we further analyzed the relationship between the throughput on the beam control channel and the number of UAVs, the formula for throughput can be expressed as

$$S_c = \frac{E[P]}{\frac{T_\sigma(1 - P_{bu})/P_{bu} + T_c}{P_{su}} + T_s + 2T_{\Delta d} - T_c}. \tag{16}$$

Let $Y = \frac{T_\sigma(1 - P_{bu})/P_{bu} + T_c}{P_{su}}$, when Y gets the minimum value τ_0, the throughput S_c gets the maximum value. The optimal solution to minimize τ_0 is given in the literature [13] as

$$\tau_0 = \frac{\sqrt{[n+2(n-1)(\overline{T}_c-1)/n-1]}}{(n-1)(\overline{T}_c-1)} \approx \frac{1}{n\sqrt{\overline{T}_c/2}}, \quad (17)$$

where $\overline{T_c} = T_c/T_\delta$, to further calculate the corresponding backoff window W_{c0}, the nonlinear system of equations consisting of (9) and (10) must be solved to obtain the approximate values of P_{co} and P_{bu}, and then W_{c0} is calculated from (8). The calculation is more difficult, and to simplify the calculation, we need to further derive the approximate expression of τ_0.

let $\rho = \sqrt{\overline{T}_c/2}$, $\left(1-\frac{1}{n\rho}\right)^n = x$, $x^\rho = \left(1-\frac{1}{n\rho}\right)^{n\rho}$, due to $T_c \gg T_\sigma$, so $n\rho$ is large enough to make the approximation of $x^\rho \approx 1/e$, $x \approx 1/\sqrt[\rho]{e}$, P_{co} and P_{bu} can be simplified as

$$P_{co} = 1-(1-\frac{1}{n\rho})^n/(1-\frac{1}{n\rho}) \approx 1-\frac{1}{\sqrt[\rho]{e}}/\left(1-\frac{1}{n\rho}\right), \quad (18)$$

$$P_{bu} = 1-(1-\frac{1}{n\rho})^n \approx 1-\frac{1}{\sqrt[\rho]{e}}. \quad (19)$$

According to (17), (18), (19) and (8), we can obtain the optimal communication backoff window $W_{c0} = W_n$ with the transmission probability τ is equal to τ_0 on the beam kth, the relationship between W_n and the number of UAVs is

$$W_n = \frac{2n\rho\frac{1}{\sqrt[\rho]{e}} - \left[\frac{2W_r}{\sqrt[\rho]{e^2}}\Big/\left(1-\frac{1}{n\rho}\right)+1\right]}{\frac{\left(\frac{1}{\sqrt[\rho]{e}}\big/\left(1-\frac{1}{n\rho}\right)\right)}{1-2\left(1-\frac{1}{\sqrt[\rho]{e}}\big/\left(1-\frac{1}{n\rho}\right)\right)} \times \frac{1-\left(2\left(1-\frac{1}{\sqrt[\rho]{e}}\big/\left(1-\frac{1}{n\rho}\right)\right)\right)^{m+1}}{1-\left(1-\frac{1}{\sqrt[\rho]{e}}\big/\left(1-\frac{1}{n\rho}\right)\right)^{m+1}}}. \quad (20)$$

Due to the sensitivity of the ISAC receiver, the UAV can accurately listen to the transmission and reception status of the beam control channel, and then obtain the number n of UAVs in a single beam, so the initial value of the backoff window can be set to W_{c0} on the kth beam to obtain the optimal throughput.

C. ISAC channel assignment scheme

Since UAVs are divided by beam in the network and the number of UAVs on a single beam is small. Therefore, a single UAV can be supported to use multiple ISAC channels for data transmission based on the packet size.

We define N_{com} as the number of ISAC channels allocated by the UAV, B_d as the transmission rate of each channel, and η as the channel efficiency. When the ISAC channel is saturated, the throughput can be expressed as

$$S_{ISAC} = \eta N_{com} B_d. \quad (21)$$

For a data packet of length $E[P]$, η can be calculated by the following formula as

$$\eta = \frac{E[P]/B_b}{T_d + E[P]/B_b}, \quad (22)$$

$$T_d = T_{delay} + T_{ACK} + 2T_{SIFS} + 2T_{radar}, \quad (23)$$

where $T_{delay} = T_s - (T_{RES} + T_{SIFS})$ represents the waiting time for transmitting a new data packet, and T_{ACK} is the transmission time of the response packet.

In contrast to conventional data channels, since integrated sensing and communication signal is transmitted on the ISAC channel, the signal echo needs to be protected from being masked by the next transmitted signal, so the time T_{radar} is reserved for the radar and the size of T_{radar} is determined according to the maximum range of the radar as

$$T_{radar} = \frac{R_{\max}}{c_0} = \sqrt[4]{\frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 \delta {c_0}^4}}, \quad (24)$$

where P_T represents the radar transmit signal power, G_T and G_R represent the transmit and receive antenna gain, λ represents the signal wavelength, σ represents the uniform radar cross section, and δ represents the radar detection threshold.

The saturated throughput of multiple access for the UAV ISAC system is subject to the dual constraints of the beam control channel and the ISAC channel, which can be written as

$$S_{mac} = \min\{S_c, S_{ISAC}\}. \quad (25)$$

According to (25), we can conclude that the critical point for the saturation of the UAV network is the saturation of the ISAC channel and the beam control channel at the same time. Therefore, we can assign the appropriate number of ISAC channels to each UAV according to the packet size, the number of corresponding channels assigned is

$$N_{com} = \left\lceil \frac{P_{bu} P_{su} (T_d + E[P]/B_b)}{P_{su} T_s + (1-P_{bu}) T_\sigma + (P_{bu} - P_{su}) T_c} \right\rceil, \quad (26)$$

where $\lceil\rceil$ represents rounding up.

IV. Simulation Results

We assume that the bandwidth of both the beam control channel and ISAC channel are 10 Mbit/s, and the packet length RTS, CTS, RES, ACK, PHY are 192 bit, 192 bit, 192 bit, 112 bit and 192 bit, the values of the constant T_{EIFS}, T_{DIFS}, T_{SIFS}, T_σ are 300μs, 50μs, 10μs, 20μs, respectively, and the maximum backoff value m is 8. Fig.4 demonstrates the throughput comparison under different backoff windows. As shown in Fig.4, after increasing the communication backoff window based on competing nodes obtained by sensing information in the ISAC system, the collision probability of nodes at the time of access is greatly decreased compared to the traditional stationary communication backoff window, and the throughput of the entire network can be significantly increased.

Fig. 5 demonstrates the relationship between the throughput of the ISAC channel and the UAV nodes at detection distances of 4 km, 8 km, and 12 km when two ISAC channels are considered. Fig. 5 shows that the throughput of the ISAC channel is affected to some extent compared to the conventional data channel due to the echoes generated by the ISAC signal, and the throughput decreases with the increase of the detection range. However, the presence of the sensing function have little

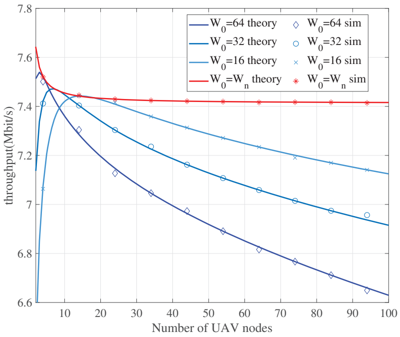

Fig. 4: Beam control channel throughput

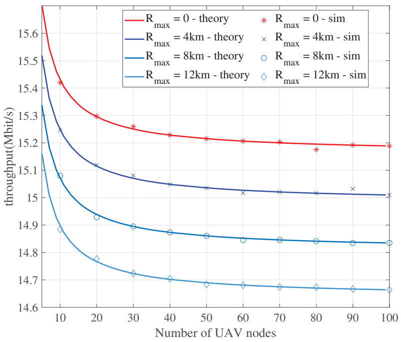

Fig. 5: ISAC channel throughput

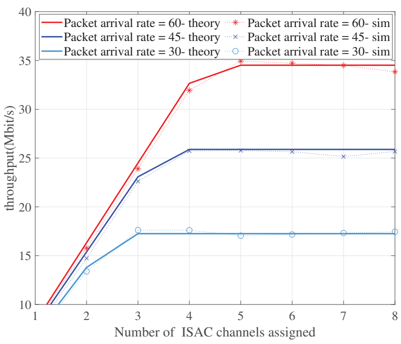

Fig. 6: UAV network throughput

effect on the throughput so that it has no significant impact on the communication transmission in the ISAC system.

Fig.6 shows that when there are fewer ISAC channels allocated to the UAV nodes, the throughput of the UAV's ISAC system is restricted by the ISAC channels. At this time, part of the reservation capacity of the beam control channel will be wasted, and as more and more ISAC channels are allocated, the throughput of the network is gradually limited by the beam control channels, and the network reaches saturation, the critical point is the optimal number of ISAC channels to be allocated, as the UAV packet arrival rate increases, the optimal number of ISAC channels for the UAV also increases.

V. Conclusion

This paper proposes a novel multiple access method for the UAV ad hoc network in the ISAC system, which aims to realize the communication between the detection UAV and the surrounding UAVs while ensuring the full-time detection of the radar. Simulation results show that sensing information can be used to reduce the number of conflicts when UAV nodes are accessed and improve the network throughput. In addition, The presence of ISAC signal echoes causes a slight decrease in the throughput of the ISAC channel and has no significant impact on the communication transmission in the ISAC system. Moreover, the dynamic ISAC channel division scheme can improve the stability of the system and ensure that the network is in an optimal state.

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