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Acknowledgement

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WEBINAR SERIES ON ADVANCED AIR MOBILITY

Joint Sensing and Communications

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Recap

UAS-to-UAS Communications

In September 2022, The Radio Technical Commission for Aeronautics (RTCA) identified five use cases for UAS to UAS communications.

1. Collision Avoidance
2. Merging.spacing and sequencing of Traffic
3. Airborne Separation
4. Airborne Rerouting
5. Sensing and Sharing of Airspace Hazard Information

IEEE P1920.2 WG is developing a standard for UAS-to-UAS Communications which is expected to be released by the end of 2023.

Key Concepts in Airspace Management

- Air Corridors: Structured airspaces reserved (to some extent) for AAM services
- Geofences: virtual three dimensional “boundaries” each UAS flies within
- UAS-to-UAS Communications: An alternative solution for traffic coordination

Challenge: Detect And Avoid
Recap

- UAV-BS/UE channel modelling and experimental verification
- 3D network modelling and performance analysis
- General UAV energy model and energy-efficient design
- Security issues in UAV communications
- Massive MIMO/mmWave for UAV swarm communications
- Low-complexity UAV trajectory/placement design
- UAV communications with limited wireless backhaul
- UAV meets wireless power/energy harvesting/caching/edge computing/intelligent reflecting surface (IRS), etc.

- UAV/LEO/Satellite integrated communication systems
  - UAV sensing and communication integrated design
  - AI for UAV communications and networking
  - UAV-5G/6G integration, standardization

Ref: Webinar by Prof Rui Zhang
Beyond 5G and towards 6G

NEXT-GENERATION wireless networks demand high-quality wireless connectivity as well as highly accurate and robust sensing capability.

*Sensing will play a more significant role than ever before.*

The close cooperation of the communication and sensing functions can enable significant improvement of *spectrum efficiency, reduction of device size, cost and power consumption* and improvement of *performance* of both functions.
Space-Air-Ground Integrated Networks

Joint (Integrated) Sensing and Communication Scenario

Sensing collects and extracts information from noisy observations.

Communication focuses on transferring information via specifically tailored signals and then recovering it from a noisy environment.

The ultimate goal is to co-design for mutual benefit

- Communication-assisted Sensing
- Sensing-assisted Communication

Application Scenarios for UAV enabled Integrated Sensing and Communication

K. Meng et al., "UAV-Enabled Integrated Sensing and Communication: Opportunities and Challenges," in IEEE Wireless Communications, April 2023
doi: 10.1109/MWC.131.2200442.

Detect and monitor suspicious UAV targets

Aerial Relays to improve coverage

---

Track location of ground receivers for better beam tracking

---

**Fig. 1.** Application scenarios for UAV-enabled ISAC.
Drone Assisted Vehicular Networks

Line-of-Sight Links which can provide higher reliability and throughput

V2V and V2I connectivity can be enhanced significantly

FIGURE 1. Drone Assisted Vehicular Networks architecture.

UAV Sensing and Transmission

1. UAV Sensing: In UAV sensing, the UAV first moves to the location that is suitable for sensing, and then hovers to perform data sensing for the task.

2. UAV Transmission: In UAV transmission, the UAV first moves to the area where the communication constraints are satisfied, and then transmits the sensory data to the BS.
Wireless Power Transfer and Path Planning for Precision Agriculture

• Charging Sensor Nodes (SNs) and collecting sensing data using UAVs. The problems of cluster head (CH) election and path planning are considered at the same time to maximize charging efficiency in a way that the lifetime of SNs can be prolonged.

UAS related Remote Sensing

Synthetic Aperture Radar (SAR) systems carried by aerial platforms using chirp or OFDM waveforms.

Communication data can be embedded into these waveforms, to broadcast low-speed data streams.

A radio sensing system and an emergency communication system can be merged to achieve higher energy and hardware efficiency.

A swarm of drones can cooperatively act as mobile antenna array.

Flying Radio Access Network (FRAN)

FRAN provides wireless connectivity to ground users by aerial base stations (BSs) that are mounted on unmanned aerial vehicles (UAVs) or balloons.

REBOT: Relaying Robot

• Autonomous flight of an aerial 5G relay providing enhanced end-to-end 5G connectivity to ground users from a terrestrial base station with an autonomous placement algorithm.
  • custom-built drone and a 5G base station based on OpenAirInterface. The ground user carries a commercial 5G module (Quectel) terminal.

Video

Radar and Communication Systems Inspire Each Other

- Triggered by MIMO communication techniques, co-located MIMO radar was proposed

- Joint Sensing and Communication schemes
  - Sensing-centric design: combining chirp signals with phase-shift keying (PSK) modulations
  - Communication-centric design: Using OFDM waveform for sensing

- Convergence of the two technologies into systems and devices, that can serve sensing and communication with a single transmission
  - Integration Gain attained by the shared use of wireless resources for dual purposes of S&C to alleviate duplication of transmissions, devices, and infrastructure
  - Coordination Gain attained from the mutual assistance between S&C
Characteristics of a Sensing System

• Sensing Performance Metrics: Detection, Estimation, and Recognition
  • Detection: Binary Hypothesis problem. Detection performance can be measured by **Probability of Detection, Probability of False Alarm**.
  • Estimation: Extracting distance/velocity/angle/quantity/size of the target(s). Estimation performance can be measured by the **Mean Squared Error (MSE) and Cramér-Rao Bound (CRB)**
  • Recognition: Defining what the target object is. Performance is based on **recognition accuracy**
Detection of UAS using mmWave Radar

Radar board was on the Ground and the UAS was flying. The maximum detection range observed in this test scenario was 40m. Experiments at Airfield in Indian Institute of Science Bangalore. 13°01’38.2”N 77°33’47.8”E

Micro-Doppler Characteristics of UAS using mmWave Radar

Fig. 4: Range-Doppler Map with UAS Trajectory

Fig. 8: Micro-Doppler Signatures From Spectrogram

We consider two UAVs with rotors whose rotation rate is 4 rad/s and having blade lengths 6 m and 8m respectively. Both two-rotor systems are 1m wide. The operating frequency of the Radar is 5 GHz.

Characteristics of Communication Sys

• Communication performance: Efficiency and Reliability
  • Efficiency: how much information is successfully delivered from the transmitter to the receiver, given limited available resources. Spectral efficiency (bit/s/Hz), energy efficiency, (bit/s/Joule), channel capacity, coverage, and the maximum number of served users are some metrics.
  • Reliability: ability of a communication system to reduce or even to correct erroneous information bits. Commonly used metrics include the outage probability, bit error rate (BER), symbol error rate (SER) and frame error rate (FER).
Information Theoretic Limits for Sensing & Communication Systems

\[
\frac{d}{d \text{snr}} I(\text{snr}) = \frac{1}{2} \text{MMSE}(\text{snr}).
\] (1)

That is, the derivative of the mutual information with respect to snr is equal to half of the MMSE regardless of the input statistics.

Each resolution unit can be considered as a binary information storage unit. Sensing capacity of an $N_t$ antenna pulsed radar

$$C_R = \log N_u.$$  

$$N_u \propto \left( \frac{D_{\text{max}}}{\Delta D} \right) \left( \frac{2\pi}{\Delta \theta} \right) \left( \frac{\text{PRF}}{\Delta f_D} \right),$$  

where $\Delta D$, $\Delta \theta$, and $\Delta f_D$ stand for the range resolution, angular resolution, and Doppler resolution of the radar, and $D_{\text{max}}$ and PRF denote the maximum detectable range and the pulse repetition frequency (PRF), respectively.

$$\Delta D = \frac{c}{2B}, \quad \Delta f_D = \frac{1}{T_d}, \quad \Delta \theta \approx \frac{2}{N_t},$$

where $B$ is the bandwidth, and $T_d$ represents the dwell time,
MIMO-OFDM Radar and Communication Systems

OFDM - Recap

Peak-to-average Power Ratio (PAPR) is high
MIMO OFDM Communication System - Recap

Mixture of signals

Mixture of signals

Mixture of signals

Mixture of signals
MIMO OFDM Communication System - Recap
MIMO OFDM Radar System - Recap

Transmitter/Receiver

Antenna

Down Converter

Carrier Frequency

Up Converter

Switch

$\sin(2\pi f_c t)$

$\sin(2\pi f_c t)$

Target with Velocity, $v$

2D

Distance (Range)

Direction

$D_M = D_1 + (M-1) d \sin \theta$

$D_{M-1}$

$D_1$

Direction

Distance (Range)

Velocity

$2D_M/c$

$t=0$

2$D_1/c$

$\tau$

$f_s, 2f_s, \ldots$

$\tau$

$f_s + f_d, 2f_s + 2f_d, \ldots$

$\tau$

$2D_M/c$

$\tau$

$2D_1/c$
MIMO-OFDM Dual Function Radar Communication (DFRC) System

Assuming the first $L$ sub-carriers are private
- private sub-carrier carrying data
- unused private sub-carrier
- shared sub-carrier carrying data

$s(u, l)$ is a vector of transmitted symbols on all sub-carriers for $u^{th}$ OFDM symbol and $l^{th}$ transmit antenna
MIMO Shared Subcarriers-OFDM (SS-OFDM) System

- Transmits OFDM waveforms, where the subcarriers are marked as shared or private by allowing antennas to simultaneously transmit on all shared subcarriers. The private subcarriers are made available to the transmit antennas to transmit in an exclusive fashion.
- Flexibly trades off communication rate for improved target estimation performance by controlling the number of private subcarriers.

Parameter Estimation in MIMO-OFDM DFRC System

Similarly, Fourier Transform of sequences across the sub-carrier domain will provide Range estimates and Fourier transform across symbols will give velocity estimates.
Subspace Methods vs Fourier Transform Methods

• For a data model having a sum of exponentials
  • Fourier Transform methods do not perform well if the frequencies are very close
  • Subspace methods like ESPRIT, MUSIC, Root-MUSIC perform well

• Subspace methods require a certain structure in the data model
Proposed Subspace Approach to Estimate Range, Velocity and Direction

• Subspace Approach has been primarily used to estimate temporal frequencies or spatial frequencies (Directions of Arrival)
• Range and Velocity are estimated using the estimated Direction via the Fourier Transform approach
• Novel waveform design to enable subspace approach for estimating range and velocity also implying that estimation accuracy can be improved significantly!
For $K$ targets, the received symbols in the frequency domain are given by [1]:

$$y(g, u, m) = \sum_{k=1}^{K} \alpha_k \left[ \sum_{l=0}^{L-1} s(g, u, l) \exp \left( -j2\pi l d \sin \theta_k \frac{(f_c + g\Delta f)}{c} \right) \right]$$

$$\times \exp \left( -j2\pi m d \sin \theta_k \frac{(f_c + g\Delta f)}{c} \right) \exp \left( -j2\pi \frac{2D_k}{c} \right) \exp(j2\pi u T f_k^d)$$

(1)

$\theta_k$ - DOA of the $k^{th}$ target; $D_k$ - range of the $k^{th}$ target; $f_k^d$ - Doppler frequency of the $k^{th}$ target

$g$ is the $g$th subcarrier in the OFDM Symbol; $u$ is the $U$th OFDM Symbol; $m$ is the $m$th antenna

$g = 1, \ldots, G;$ $u = 1, \ldots, U;$ $m = 1, \ldots, M$


Insights for Range

For $K$ targets, the received symbols in the frequency domain are given by [1]:

$$y(g, u, m) = \sum_{k=1}^{K} \alpha_k \left[ \sum_{l=0}^{K-1} s(g, u, l) \exp \left( -j2\pi l d \sin \theta_k \left( \frac{f_c + g \Delta f}{c} \right) \right) \right]$$

$$\times \exp \left( -j2\pi m d \sin \theta_k \left( \frac{f_c + g \Delta f}{c} \right) \right) \exp \left( -j2\pi g \Delta f \frac{2D_k}{c} \right) \exp(j2\pi u T f_k^d)$$

$\theta_k$ - DOA of the $k^{th}$ target; $D_k$ - range of the $k^{th}$ target; $f_k^d$ - Doppler frequency of the $k^{th}$ target

The **target range** introduces a phase shift in the expression of the received signal, $y(g, u,m)$ in the frequency domain, i.e., **across g**.
Insights for Velocity

For $K$ targets, the received symbols in the frequency domain are given by [1]:

$$y(g,u,m) = \sum_{k=1}^{K} \alpha_k \left[ \sum_{l=0}^{L-1} s(g,u,l) \exp \left( -j2\pi ld \sin \theta_k \left( \frac{f_c + g\Delta f}{c} \right) \right) \right]$$

$$\times \exp \left( -j2\pi md \sin \theta_k \left( \frac{f_c + g\Delta f}{c} \right) \right) \exp \left( -j2\pi g\Delta f \frac{2D_k}{c} \right) \exp(j2\pi u T f_k^d)$$  \hspace{1cm} (1)

- $\theta_k$ - DOA of the $k^{th}$ target;
- $D_k$ - range of the $k^{th}$ target;
- $f_k^d$ - Doppler frequency of the $k^{th}$ target.

The **Doppler frequency or the velocity of the target** introduces a progressive phase shift in the expression of the received signal, $y(g, u,m)$ along the time domain, i.e., **along u**.

Insights from data model

For $K$ targets, the received symbols in the frequency domain are given by [1]:

$$y(g, u, m) = \sum_{k=1}^{K} \alpha_k \left[ \sum_{l=0}^{L-1} s(g, u, l) \exp \left( -j2\pi l d \sin \theta_k \frac{(f_c + g\Delta f)}{c} \right) \right]$$

$$\times \exp \left( -j2\pi m d \sin \theta_k \frac{(f_c + g\Delta f)}{c} \right) \exp \left( -j2\pi g \Delta f \frac{2D_k}{c} \right) \exp(j2\pi u T f_{kd}^d)$$

(1)

$\theta_k$ - DOA of the $k^{th}$ target; $D_k$ - range of the $k^{th}$ target; $f_{kd}^d$ - Doppler frequency of the $k^{th}$ target

For a fixed sub-carrier and a fixed OFDM symbol, the DOA of the target introduces a progressive phase shift in the expression of the received signal, $y(g, u, m)$ along the antennas in the spatial domain, i.e., along $m$.

To estimate the range, the equation (7) can be rewritten as follows:

$$y(g, u, m) = a^T_D(g)\Psi(g, u, m)\Lambda^T_\theta(g)s(g, u) + \eta(g, u, m)$$  \hspace{1cm} (20)

where $a_D(g)$ is given by:

$$a_D(g) = \left[\exp\left(-j2\pi g\Delta f \frac{2D_1}{c}\right) \ldots \exp\left(-j2\pi g\Delta f \frac{2D_K}{c}\right)\right]^T$$  \hspace{1cm} (21)

In addition, the matrix $\Psi(g, u, m)$ is defined by:

$$\Psi(g, u, m) = \text{diag} \left[\alpha_1 \exp\left(j2\pi u T f_1^d\right)\exp\left(-j\omega_1(g)\right) \ldots \alpha_K \exp\left(j2\pi u T f_K^d\right)\exp\left(-j\omega_K(g)\right)\right]$$  \hspace{1cm} (22)

Proposed Waveform Design for Range

Assumption 1: Let us approximate \( f_g \) by \( f_c \) \( \forall g = 0, 1, \cdots, G - 1 \). This approximation is valid as \( \Delta f \ll f_c \) for any \( g \). In that case, \( \Psi(g, u, m) \) and \( A_g^T(g) \) no longer depend on \( g \).

Assumption 2: For a fixed transmit antenna \( l \), the data symbols transmitted on a fixed OFDM symbol \( u \) are assumed to be the same for all the sub-carriers for the subspace methods to be applicable. Mathematically, this means for \( l = 0, 1, \cdots, L - 1 \) and \( u = 0, 1, \cdots, U - 1 \):

\[
 s(0, u, l) = s(1, u, l) = \cdots = s(G - 1, u, l) \tag{23}
\]

The vector \( s(g, u) \) is hence the same for all values of \( g \) and can be represented as \( s(u) \).

Therefore, the subspace methods like MUSIC, Root-MUSIC and ESPRIT are applicable to estimate the DOA of K targets from the full rank correlation matrix $R_D(u,m)$. 

\[
R_D(u,m) \approx \sigma_s^2 A_D(G) \Psi(u,m) A_\theta^T A_\theta^* \Psi^H(u,m) A_D^H(G') + \sigma_\eta^2 I_G
\]

The matrices $\Psi(u,m)$, $A_D(G)$ and $A_\theta$ have consequently a full rank, equal to $K$. The signal subspace associated with the correlation matrix equal to $\sigma_s^2 A_D(G') \Psi(u,m) A_\theta^T A_\theta^* \Psi^H(u,m) A_D^H(G')$ is of dimension $K$. 

To estimate the target velocity, the equation (7) is written as:

\[ y(g, u, m) = a_v^T(u)\chi(g, m)A_\theta^T s(g, u) + \eta(g, u, m) \]  

(30)

where \( a_v(u) \) is given by:

\[ a_v(u) = \left[ \exp(j2\pi u T f_1^d) \ldots \exp(j2\pi u T f_K^d) \right]^T \]  

(31)

Given \( \omega_k \) whose expression is given in (11), the matrix \( \chi(g, m) \) is defined as:

\[ \chi(g, m) = \text{diag} \left[ \alpha_1 \exp(-j2\pi g \Delta f \frac{2D_1}{c}) \exp(-j\omega_1(g)) \ldots \alpha_K \exp(-j2\pi g \Delta f \frac{2D_K}{c}) \exp(-j\omega_K(g)) \right] \]  

(32)

Waveform Design to Estimate Velocity

In the following, let us look at the assumption one could make to use subspace methods to estimate the velocity.

Assumption: For a fixed transmit antenna $l$, the data symbols transmitted on a fixed sub-carrier frequency $f_g$ are assumed to be the same during all OFDM symbols for the subspace methods to be applicable. Mathematically, this means for $l = 0, 1, \ldots, L - 1$ and $g = 0, 1, \ldots, G - 1$:

$$s(g, 0, l) = s(g, 1, l) \cdots = s(g, U - 1, l)$$

(33)

Estimating Velocity

\[ R_v(g, m) = \sigma_s^2 A_v(U) \chi(g, m) A_\theta^T A_\theta^* \chi^H(g, m) A_v^H(U) + \sigma_\eta^2 I_U \]

linearly independent. The matrices \( \chi(g, m) \), \( A_v(U) \) and \( A_\theta \) have consequently a full rank, equal to \( K \). The signal subspace associated with the correlation matrix equal to \( \sigma_s^2 A_v(U) \chi(g, m) A_\theta^T A_\theta^* \chi^H(g, m) A_v^H(U) \) is of dimension \( K \). Therefore,

Therefore, the subspace methods like MUSIC, Root-MUSIC and ESPRIT are applicable to estimate the DOA of \( K \) targets from the full rank correlation matrix \( R_v(g,m) \).

Estimating Direction

For example, the received data over the $g^{th}$ sub-carrier related to the $u^{th}$ OFDM symbol is stacked over the $M$ antennas results in:

$$y(g, u) = \left[ y(g, u, 0) \quad \ldots \quad y(g, u, M - 1) \right]^T$$

(8)

$$y(g, u) = A_{\theta}(g, M) \Phi(g, u) A_{\theta}^T(g, L) s(g, u) + \eta(g, u)$$

$$R_{\theta}(g, u) = \mathbb{E}[y(g, u)y^H(g, u)]$$

(17)

$$= A_{\theta}(g) \Phi(g, u) A_{\theta}^T(g) R_s(g, u) A_{\theta}^* (g) \Phi^H(g, u) A_{\theta}^H(g) + \sigma^2_{\eta} \mathbf{I}_M$$

Therefore, the subspace methods like MUSIC, Root-MUSIC and ESPRIT are applicable to estimate the DOA of $K$ targets from the full rank correlation matrix $R_{\theta}(g, u)$.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbols</th>
<th>Parameters</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of transmit antennas</td>
<td>$L$</td>
<td>Velocity of the $k^{th}$ target</td>
<td>$v_k$</td>
</tr>
<tr>
<td>Index of the transmit antenna</td>
<td>$l = 0, \ldots, L - 1$</td>
<td>Doppler frequency of the $k^{th}$ target</td>
<td>$f_k^d$</td>
</tr>
<tr>
<td>Number of receive antennas</td>
<td>$M$</td>
<td>Constellation order for modulation</td>
<td>$B$</td>
</tr>
<tr>
<td>Index of the receive antenna</td>
<td>$m = 0, \ldots, M - 1$</td>
<td>Number of sub-carriers</td>
<td>$G$</td>
</tr>
<tr>
<td>Distance between two consecutive</td>
<td>$d$</td>
<td>Index of the sub-carrier</td>
<td>$g = 0, \ldots, G - 1$</td>
</tr>
<tr>
<td>transmit/receive antennas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of targets</td>
<td>$K$</td>
<td>Number of OFDM symbols</td>
<td>$U$</td>
</tr>
<tr>
<td>Index of the target</td>
<td>$k = 1, \ldots, K$</td>
<td>Index of the OFDM symbol</td>
<td>$u = 0, \ldots, U - 1$</td>
</tr>
<tr>
<td>DOA of the $k^{th}$ target</td>
<td>$\theta_k$</td>
<td>Duration of the OFDM symbol</td>
<td>$T$</td>
</tr>
<tr>
<td>Range of the $k^{th}$ target</td>
<td>$D_k$</td>
<td>Duration of the cyclic prefix</td>
<td>$T_{CP}$</td>
</tr>
</tbody>
</table>

Table 1: System parameters and the corresponding notations

<table>
<thead>
<tr>
<th>Index</th>
<th>Assumption on transmitted data</th>
<th>Interpretation</th>
<th>Potential approaches that can be used to estimate DOA-range-velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Model 1</td>
<td>No assumption on $s(g, u, l) \forall g, u$ and $l$</td>
<td>The transmitted data are different over all sub-carriers, OFDM symbols and antennas. All sub-carriers are shared.</td>
<td>SS-TLS-TLS (proposed) FT-FT-FT [19]</td>
</tr>
<tr>
<td>Data Model 2</td>
<td>$s(0, u, l) = s(1, u, l) \cdots = s(G - 1, u, l) \forall u$ and $l$</td>
<td>The transmitted data are the same over all sub-carriers. All sub-carriers are shared.</td>
<td>SS-SS-TLS (proposed) SS-TLS-TLS (proposed) FT-FT-FT [19]</td>
</tr>
<tr>
<td>Data Model 3</td>
<td>$s(g, 0, l) = s(g, 1, l) \cdots = s(g, U - 1, l) \forall g$ and $l$</td>
<td>The transmitted data are the same over all OFDM symbols. All sub-carriers are shared.</td>
<td>SS-TLS-SS (proposed) SS-TLS-TLS (proposed) FT-FT-FT [19]</td>
</tr>
<tr>
<td>Data Model 4</td>
<td>$s(0, u, l) = s(1, u, l) \cdots = s(G - 1, u, l) \forall g, u$, and $l$</td>
<td>The transmitted data are the same over all sub-carriers and all OFDM symbols. All sub-carriers are shared.</td>
<td>SS-SS-SS (proposed) SS-SS-TLS (proposed) SS-TLS-SS (proposed) FT-FT-FT [19]</td>
</tr>
</tbody>
</table>

Let $G$ be the set of private sub-carriers. For $g \in G$, $s(g, u, l) \neq 0$ if the $g$th sub-carrier is paired to the $l$th transmit antenna. Otherwise, $s(g, u, l) = 0$. For $g \notin G$, no assumption on $s(g, u, l) \forall u$ and $l$.

A set of $L$ sub-carriers among $G$ sub-carriers are private while remaining sub-carriers are shared. Data transmitted over all sub-carriers, OFDM symbols and transmit antennas are different.

Table 2: Assumptions on the transmitted data and corresponding usable approaches among the proposed and the existing approaches.
Figure 3: DOA, range and velocity estimates from SS-SS-SS, SS-SS-TLS, SS-TLS-SS, SS-TLS-TLS and FT-FT-FT based on data model 4 for 100 trials and 10 snapshots at $(\text{SNR}_1, \text{SNR}_2) = (20, 20)$ dB. True targets parameters are $(39.32^\circ, 153.73 \text{ m}, 31.72 \text{ m/s})$ and $(49.32^\circ, 903.73 \text{ m}, 81.72 \text{ m/s})$.

Summary

• Sharing the spectrum and hardware is critical for efficient use of resources

• Estimating the position and other relevant parameters of UAS is critical for joint sensing and communication networks
Open Problems to be addressed

• Correlation Model Between S&C Channels for sensing-assisted communication designs
• Quantitative Description of Coordination Gain
• ISAC Frame Protocol Design for unified ISAC waveforms or beams
• Joint Resource Allocation, Waveform, and Deployment/Trajectory Design
• Coordinated Interference Management
• Cooperative ISAC
• IRS-assisted UAV-enabled ISAC
• Secure UAV ISAC
• AI for UAV ISAC Design
• ...

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