Art of Marriage: Performance Trade-offs and Waveform Synthesis in Integrated Sensing and Communications

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Outline

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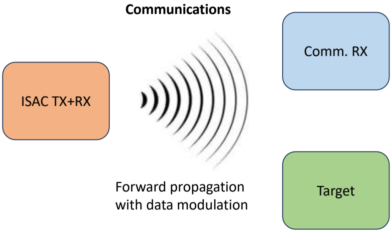
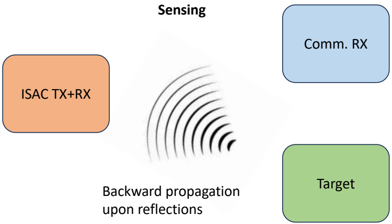
Integrated Sensing and Communications



- Communications and radar are major consumers of wireless spectrum that is facing resource shortage. It improves the efficiency to share the spectrum between communications and radar.
- In Integrated Sensing and Communications (ISAC), the waveform completes communications in the forward propagation, and then sensing in the backward propagation.

Integrated Sensing and Communications



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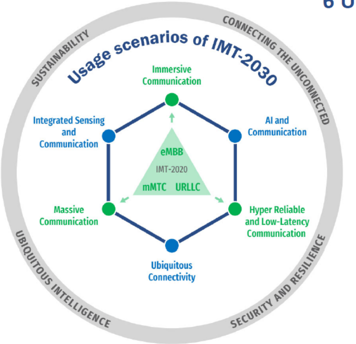
ISAC As A Pilar of 6G

Usage scenarios



So called "Wheel diagram"

6 Usage scenarios

Extension from IMT-2020 (5G)

- eMBB ➡ Immersive Communication
- mMTC ➡ Massive Communication
- URLLC ➡ HRLLC (Hyper Reliable & Low-Latency Communication)

New

- Ubiquitous Connectivity
- AI and Communication
- Integrated Sensing and Communication

4 Overarching aspects:

act as design principles commonly applicable to all usage scenarios

Sustainability, Connecting the unconnected,
Ubiquitous intelligence, Security/resilience

Outline

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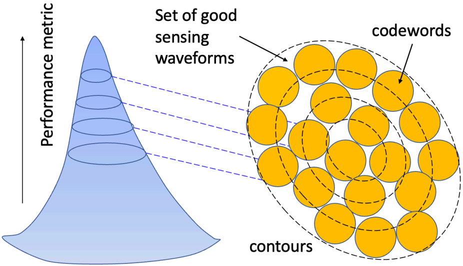
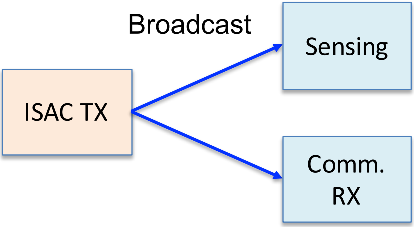
Sphere Packing Picture



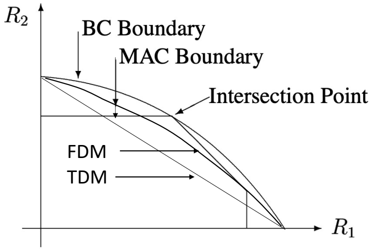
- A single waveform cannot send out communication information.
- There are N waveforms in the signal set. The selection of waveform to transmit conveys $\log_2 N$ bits.
- Each waveform is a codeword. The design of codebook in ISAC is essentially sphere packing.

Broadcast Channel Modeling



- We can consider JCS as broadcasting information to a virtual sensing user and a concrete communication user.
- Pros: Many techniques in the study of broadcast channels, such as TDM, FDM, linear precoding, or DPC, can be leveraged.
- Cons: The virtual sensing 'user' is not a real one, thus needing extra exploration and special handling.

Typical Broadcast Methodologies[1]

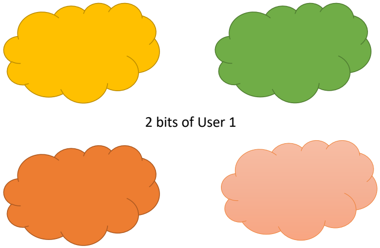


- TDM: Separated in the time, which mainly concerns the MAC layer scheduling[a].
- FDM: Separated in the frequency. Studied in our other papers.
- Superposition Coding: We design the sensing waveforms first and then transform them to superimpose the communication message.

[a] H. Li, "MAC scheduling in joint communications and sensing networks based on virtual queues," IEEE Conference on Global Communications, 2022.

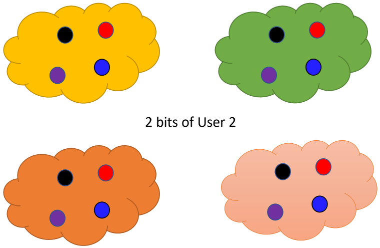
[1] H. Li, "Feasible region in joint communications and sensing: A broadcast channel framework," IEEE Globecom, 2023

Superposition Coding



- The message of User 1 is encoded into clouds (4 clouds for 2 bits).
- The message of User 2 is encoded as nuclei at each cloud (4 nuclei for 2 bits).

Superposition Coding



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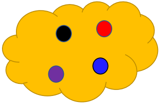
Superposition Coding: Decoding

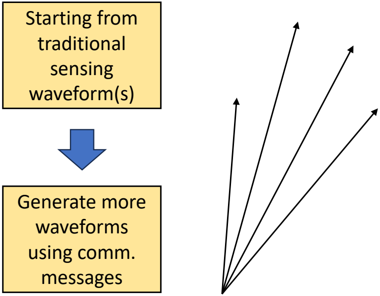


- User 1 estimates the identity of cloud and retrieves the bits.
- User 2 estimates the cloud first, and then figures out the nuclei for retrieving the bits.

Superposition Coding: Decoding

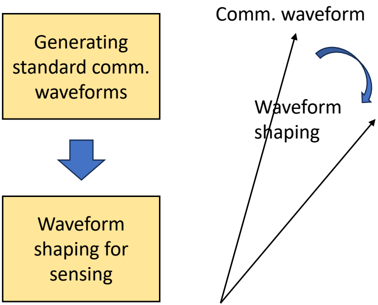
- User 1 estimates the identity of cloud and retrieves the bits.
- User 2 estimates the cloud first, and then figures out the nuclei for retrieving the bits.

Sensing-Centric ISAC



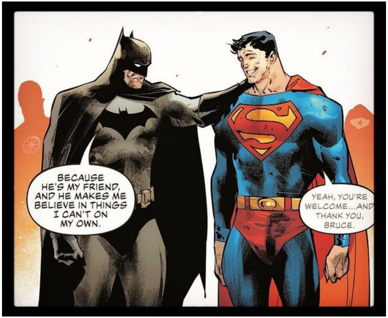
- User 1: sensing; User 2: communications.
- We design the set of sensing waveform first (e.g., using different phase codes, or transforming a prototype waveform).
- Then, communications are carried out by selecting one of the waveforms.
- Possible designs: watermarking in existing radar waveforms.

Communication-Centric ISAC



- User 1: communications; User 2: sensing.
- We first generate standard communication waveforms such as OFDM or OTFS.
- Then, the waveform is reshaped for improving the sensing performance (e.g., reducing the sidelobes).
- Possible designs: PSD windowing or trellis shaping.

Going Beyond Broadcast Modeling

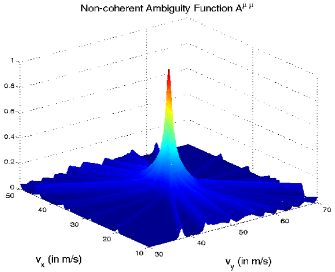


- In broadcast channel, the communications to different users are a zero-sum game. In ISAC, sensing and communications are beneficial to each other.
- Sensing provides physical information for communications, thus helping beamforming and interference mitigation,
- Communication signals provide power and bandwidth for sensing (e.g., the Wi-Fi sensing).

Outline

1. Motivation of ISAC
2. **Fundamental Views and Trade-offs**
   - Different Views of ISAC
   - Fundamental Performance Trade-offs
3. ISAC Algorithm Design
4. Conclusions and Future Work

Design and Performance Metrics



- Communications: We can use channel capacity to measure the data rate.
- Sensing: For a generic signal x, the corresponding ambiguity function is defined as

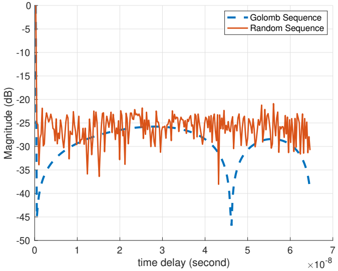
$$\chi(\tau, f) = \int_{-\infty}^{\infty} x(t)x^*(t-\tau)e^{-j2\pi f(t-\tau)}dt,$$

  where τ is time delay and f is the frequency offset.
- It is important to suppress sidelobes $\chi(\tau, 0)$ in order to detect weak targets.

Bitter Conflicts of Interests

- Communications and sensing have different purposes and characteristics, thus resulting conflicts in the waveform synthesis, as well as the networking of ISAC:
  - Waveform sensitivity to environment
  - Sensing uncertainty caused by communication randomness
  - Complexity of EM field
  - et al

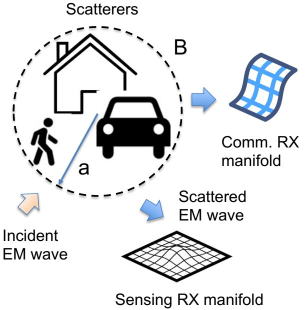
Sensing Uncertainty due to Data Randomness[2]



- In traditional radar sensing, the waveform is dedicatedly designed and deterministic (e.g., the Golomb code).
- In ISAC, we can use the communication waveform for sensing, which is pseudo-random (known to the transmitter).
- Compare the sidelobes of Golomb code and OFDM communication waveform: the randomness of waveform degrades the performance of sensing.

[2] H. Li, "Conflict and trade-off of waveform uncertainty in joint communication and sensing systems," IEEE International Conference on Communications (ICC), 2022.

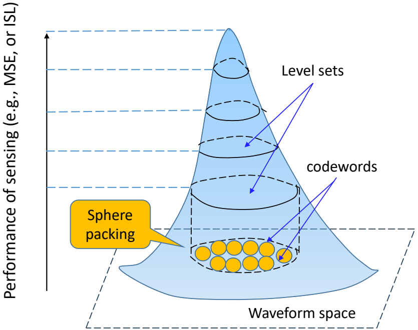
EM Field Complexity[3]



- A higher Degrees of Freedom (DoF) of EM field provides more independent channels for communications, thus higher data rate.
- A higher DoF of EM field brings more burdens to radar sensing.
- A trade-off exists between communications and sensing in terms of EM field DoF.

[3] H. Li, “Degrees of freedom in scattered field for trade-off in joint communications and sensing,” IEEE International Conference on Communications (ICC), 2022

Sphere Packing[4]



- For generic sensing performance metrics, we can consider the level sets of sensing waveforms, given a tolerable performance degradation.
- For the waveform set satisfying the performance degradation, we can use sphere packing argument to find bounds for the data communication rate, thus finding a trade-off between communications and sensing.

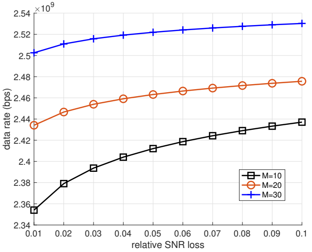
[4]H. Li, Z. Han and H. V. Poor, "Sphere packing analysis for performance trade-off in joint communications and sensing-Part I: General principle," IEEE ICC, 2024.

Rate-SNR Trade-off[5]

- The major challenge is the high-dimensional volume evaluation.
- Consider waveforms with N chips (fast time) and M communication symbols (slow time). The sensing performance metric is the SNR.
- The data rate R_1 with suboptimal waveforms is given by (when $\delta\gamma$ is small)

$$R_1 \geq R_0 + \log_2 C_0 + N \log_2 \delta\gamma,$$

where R_0 is the maximum data rate using optimal sensing waveforms, $\delta\gamma = \frac{\gamma_{\max} - \gamma}{\gamma_{\max}}$ is the SNR loss for sensing and C_0 is determined by the system parameters.



- The data rate increases versus the sensing SNR drop in a logarithmic way.

[5] H. Li, Z. Han and H. V. Poor, "Sphere packing analysis for performance trade-off in joint communications and sensing-Part II: Fourier analysis of volume," IEEE ICC, 2024.

Outline

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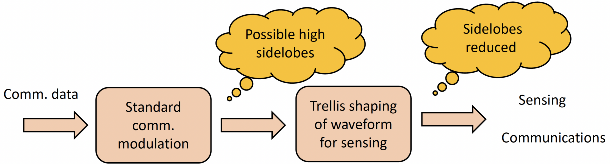
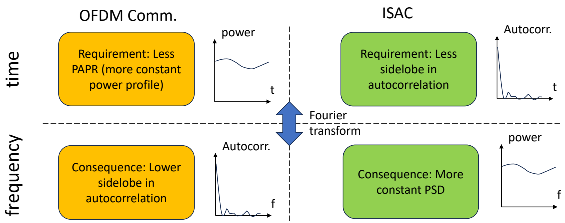
Comm-Centric Scheme 1: Trellis Shaping[6]



- The transmitter generates standard communication waveforms (e.g., OFDM), and then uses trellis-shaping to refine the waveform, in order to improve the sensing performance (e.g., lower sidelobes).
- This is similar to the reduction of Peak-Average-Power Ratio (PAPR) in 4G and 5G OFDM modulation.

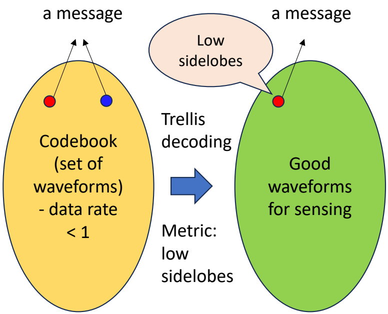
[6] H. Li, Z. Han and H. V. Poor, "Trellis shaping for joint communications and sensing: A duality to PAPR reduction," IEEE Symposium on JC&S, 2024

Duality to PAPR Reduction



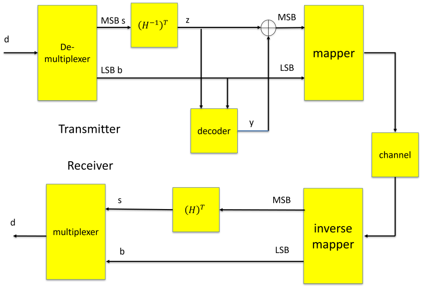
- Autocorrelation and power profile are a Fourier transform pair.
- Sidelobe (PAPR) reduction in ISAC (OFDM) needs lower sidelobes in the time-domain autocorrelation (more constant time-domain power profile) and thus more constant PSD (lower sidelobes in frequency-domain autocorrelation). The two tasks are dual to each other.

Trellis Shaping



- With data rate less than 1, we prepare a codebook of convolutional (trellis) code.
- Given a message, the Viterbi algorithm is used to select a codeword with good sensing performance (e.g., lower sideblobes).
- The sensing performance is refined at the cost of lower data rate.

Trellis Shaping



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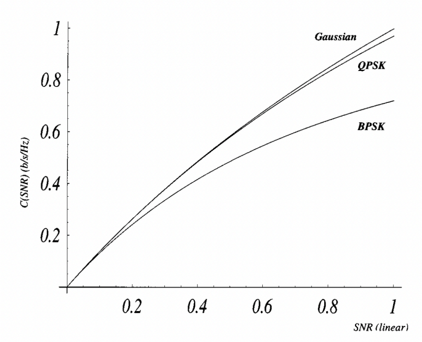
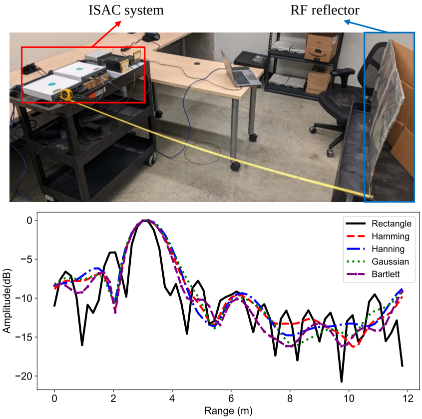
Comm-Centric Scheme 2: QPSK Modulation and PSD Shaping[7]



- We propose to use OFDM signaling: QPSK modulation over each subcarrier and window masking for the subcarrier powers.
- In the wideband regime, QPSK is shown to be asymptotically optimal for the spectral efficiency.
- The time autocorrelation (thus the sidelobes) is determined by the PSD, which can be shaped using window functions.

[7] H. Li, "Spectral efficiency in wideband joint communications and sensing: Is OFDM+QPSK (near) optimal?" IEEE ICC, 2024.

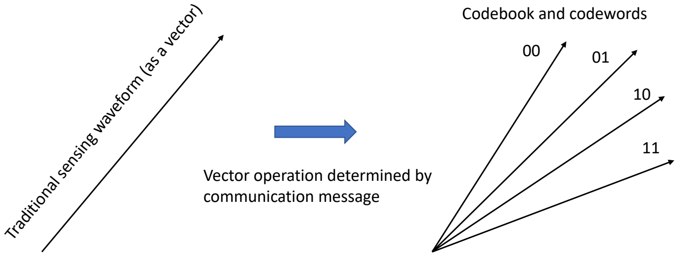
Experimental Results



- We used USRP X410 to build an ISAC system, with OFDM signaling and 200MHz bandwidth.
- Various windows are used for 64 subcarriers of OFDM. The autocorrelation function has been calculated using the received signals.
- In the experiment results, the Bartlett window has the lowest sidelobes, while the rectangle window has the highest.

Outline

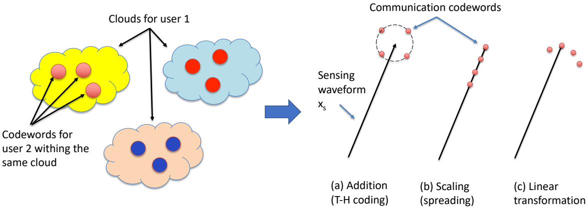
Superposition Coding Schemes for ISAC[8]



- We first generate the sensing waveform as a vector (as the cloud), or multiple sensing waveforms (for radar waveform diversity, as clouds).
- Then, the communication message is modulated over the vector operation of the sensing waveform.

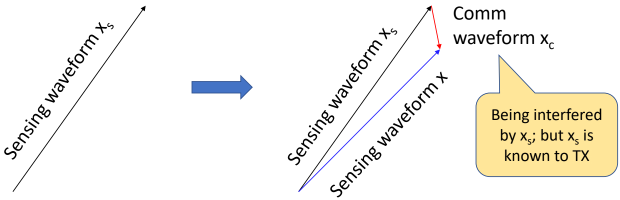
[8] H. Li, "Functional multiplexing in joint communications and sensing: A superposition coding framework," IEEE Globecom, 2023.

Superposition Coding Schemes for ISAC



- Addition - Dirty paper coding: The clouds are formed by adding communication signals to sensing signal.
- Scalar Multiplication - Spectrum spreading: The clouds are formed by multiplying communication symbols on the sensing signal.
- Matrix Multiplication (Linear transformation) - OFDM+QPSK: The communication message is encoded in the linear transformation matrix.

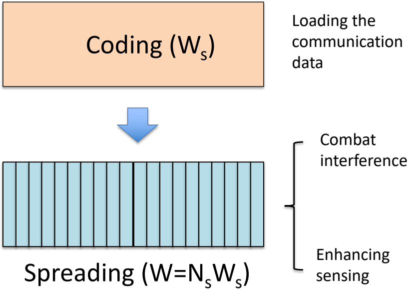
Addition: Dirty Paper Coding[9]



- We can superimpose the communication message x_c to the sensing waveform x_s.
- The signal sent out is $x = x_s + x_c$. x_s is a KNOWN interference to x_c. We can use dirty paper coding to generate x_c based on the communication message and x_s, such that the interference from x_s can be eliminated at the receiver.

[9] H. Li, "Dirty paper coding for waveform synthesis in integrated sensing and communications: A broadcast channel approach," IEEE International Conference on Communications, 2022

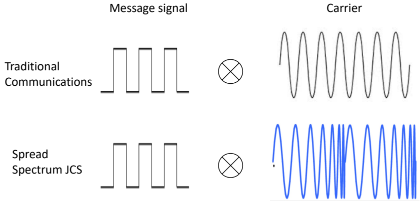
Scalar Multiplication: Spectrum Spreading[10]



- We generate the sensing waveform $\mathbf{x}_s$ (vector) and communication symbol x_c (scalar). The transmitted signal is given by $\mathbf{x} = x_c\mathbf{x}_s$.
- This is essentially spectrum spreading (CDMA), where $\mathbf{x}_s$ plays the role of spreading code.

[10]H. Li, "Interference mitigation in joint communications and sensing-Part I: Correlation and collision," the 3rd IEEE International Symposium on Joint Communications & Sensing, 2023

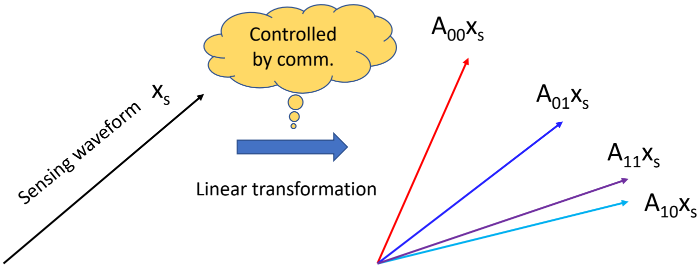
Using Sensing Waveform As Carrier[11]



- Using sensing waveform as carrier can achieve the goals of improving sensing performance and combating interference.
- A coding-spreading trade-off exists between communications and sensing, in terms of the length of sensing waveform.

[11] H. Li, "Interference mitigation in joint communications and sensing-Part II: Coding-Spreading Trade-off," the 3rd IEEE International Symposium on Joint Communications & Sensing, 2023

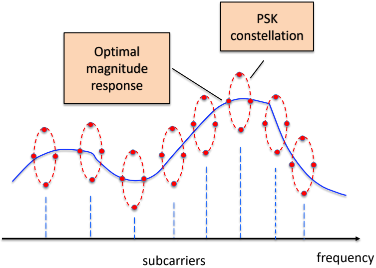
Linear Transformation



- The transmitted signal is given by $\mathbf{x} = A_{b_1,\ldots,b_n}\mathbf{x}_s$, and the selection of linear transformation matrix A is determined by n bits $b_1, \ldots, b_n$.
- The mapping from $b_1, \ldots, b_n$ to A is flexible. We consider transforming waveforms constructed from optimal filtering for radar[12].

[12] H. Li, "Waveform synthesis for MIMO joint communications and sensing with clutters-Part I: Space-time-frequency filtering," IEEE International Conference on Communications, 2023.

Linear Transformation: OFDM+QPSK[13]



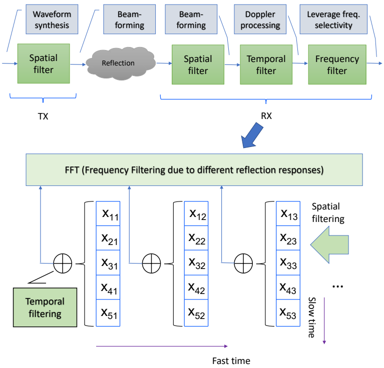
- The linear transform is given by

$$\mathbf{A} = \mathbf{F}^{-1}\Lambda\mathbf{F},$$

  where **F** is the Fourier transform matrix and $\Lambda = diag(e^{\theta_1}, ..., e^{\theta_n})$ is the PSK modulation.
- Using OFDM, we specify the amplitude of the subcarriers using the sensing filters and modulate the phases over the subcarriers.
- We can extend to the traditional structure of spatial+temporal+frequency filtering in radar systems.

[13] H. Li, "Waveform synthesis for MIMO joint communications and sensing with clutters-Part I: Spatial-Time-Frequency Filtering," IEEE International Conference on Communications, 2023.

Linear Transformation: OFDM+QPSK[14]



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[14] H. Li, "Waveform synthesis for MIMO joint communications and sensing with clutters-Part II: Bits through filter design," IEEE International Conference on Communications, 2023.

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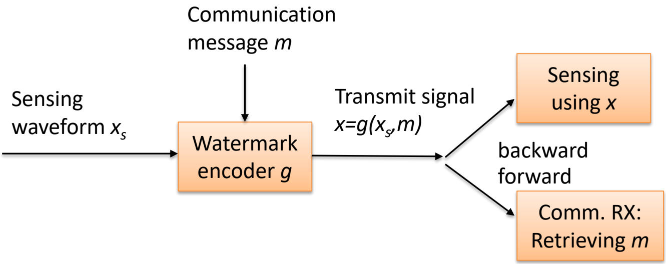
Nonlinear Mapping: Watermarking[15]

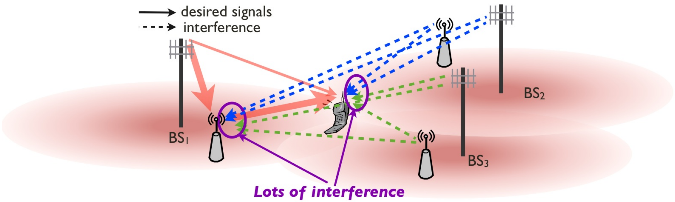


- We consider the traditional sensing waveform (e.g, the FMCW waveform) as the host signal, and communication message as the watermark.
- The communication message is embedded into the host sensing waveform, with a minimum distortion.

[15] H. Li, "Watermarking based waveform synthesis in joint communications and sensing," IEEE Global Communications Conference, 2023.

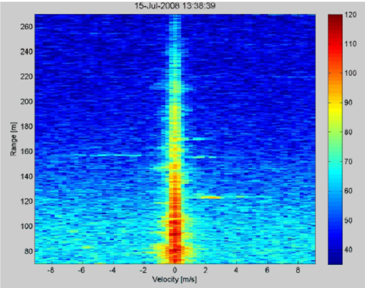
Outline

Interference Mitigation in Wireless Networks



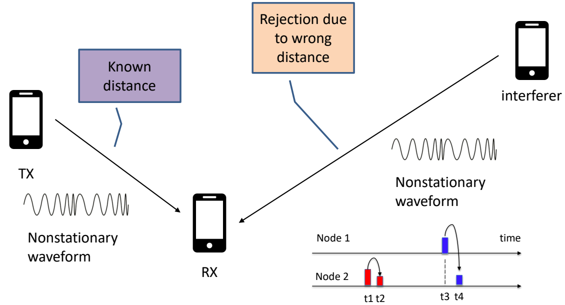
- Interference, as co-channel signals of other users, is a major challenge in wireless communication networks.
- In existing communication systems, interference is mitigated either in the MAC layer by scheduling, or in the PHY layer by signal processing (e.g., multiuser detection).
- Can we do better when the communication users know more physical information?

Physical Information for Interference Mitigation



- Angle: We can use beamforming to avoid interference from different angles (used in practice).
- Range: If the receiver knows the range to the transmitter, it can reject signals from other transmitters with different ranges.
- Doppler shift: A receiver can reject interference from transmitters with different moving speeds (similarly to clutter mitigation in radar systems).

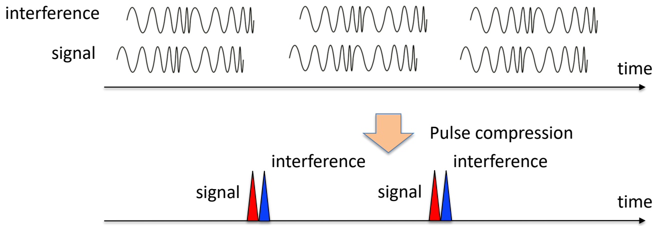
Interference Elimination Based on Ranging [16]



- Using ISAC, the receiver knows the distance to the transmitter and thus the signal propagation time.
- Then, interference beyond a certain time window is rejected.

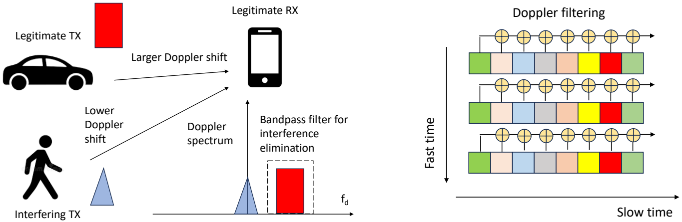
[16] H. Li, “ISAC-motivated interference elimination in wireless communication networks: A pulse compression approach,” IEEE Globecom, 2023

Long-duration Waveforms



- When the length of waveform is comparable to the time gaps of legitimate signal and interference, the interference will be mixed with the signal.
- Thanks to ISAC, the waveforms are non-stationary (otherwise, ranging cannot be accomplished), thus facilitating pulse compression that turns long waveforms into narrow pulses.

Interference Elimination Based on Doppler Shift[17]

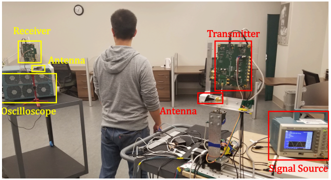


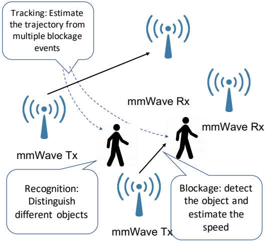
- We can further use the difference of transmitter and interferer in the Doppler domain, similarly to the clutter mitigation.
- The temporal filtering (in the slow time domain) needs to be employed.

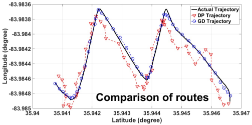
[17] H. Li, "Interference elimination via doppler filtering in joint communication and sensing networks," submitted to IEEE Globecom, 2024

Outline

Experiment 1: Tracking via Blockage of mmWave Communications[18]







- Millimeter wave is very sensitive to blockages, which also leave information about the moving object.
- We have carried out experiments in our 60GHz testbed.

[18] Z. Zhang, J. Bao, Y, Fan, and H. Li, “Tracking via blocking in millimeter wave communication networks,” in *Proc. of IEEE International Conference on Communications*, 2018.

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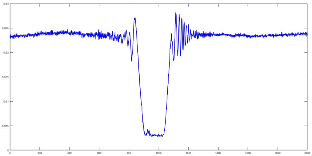
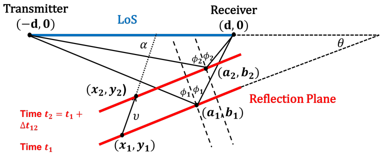
Experiment 2: Speed Estimation via mmWave Blockage





- We have observed oscillations before and after the blockage, which is due to reflection and interference.
- We can estimate the speed of the moving object by solving nonlinear equations. Experiment shows that the estimation error of speed is around 10% for pedestrians.

Experiment 3: Estimating Wind Speed Using mmWave Communications[19]

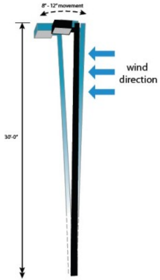
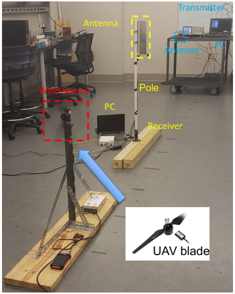


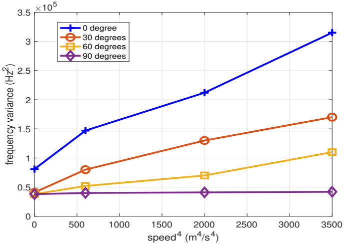
Figure 1: Observed light pole movement.

- Outdoor millimeter wave transceivers may be mounted to lamp post or tall building.
- The oscillation due to wind makes the phases incoherent (a displacement of 1mm causes a 20% change of phase in the 60GHz band).
- The velocity of transceiver due to the oscillation incurs Doppler shift of frequency, or equivalently phase modulation.

[19] Z. Zhang, J. Bao, Y. Fan and H. Li, "Sensing wind velocity by leveraging millimeter wave communications," IEEE DySPAN, 2019.

Experiment 3: Gone with Wind

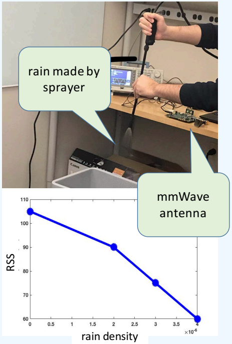




- We have tested the frequency/phase oscillation, with winds from different directions.
- It is demonstrated that the variance of frequency is approximately proportional to v_{wind}^4.

More Experiments[20]

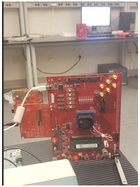
Rain Gauge Using mmWave



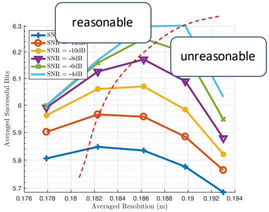
Comm. Using FMCW Radar

Transmission Power (P_t)	12dBm	Wave length (λ)	0.004m
Receiver Gain (G_r)	10dB	Transmitter Gain (G_t)	10dB
Bandwidth (B)	4GHz	Noise Figure (F)	15dB
Sampling Rate (f_s)	20 M/s	Chirp Interval (T)	100 us

System parameters



Experiment



Trade-off curves

[20] Y. Fan, J. Bao, M. S. L. Aljumaily and H. Li, “Communications via frequency-modulated continuous-wave radar in millimeter wave band,” IEEE Globecom, 2019

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Outline

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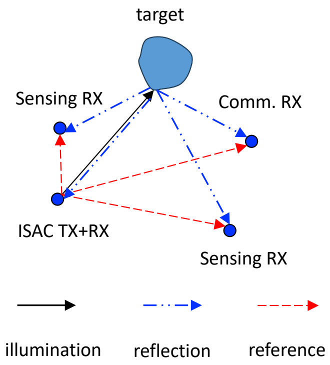
Conclusions

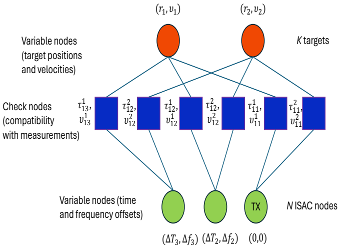
- Communication and sensing are reasonably compatible.
- Broadcast channel is a good framework to integrate both functions.
- Various trade-offs need to be identified and reconciled.

Future Work: Multi-Static ISAC



- We consider the collaborations among the transmitter, communication receiver and other sensing receivers.
- The major challenge is the time and frequency offsets that can hardly be addressed by using GPS reference synchronization.
- We propose to leverage the redundancy in the observations and the mechanism of message passing.

Future Work: Multi-Static ISAC



- We consider the collaborations among the transmitter, communication receiver and other sensing receivers.
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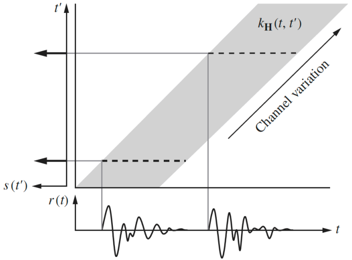
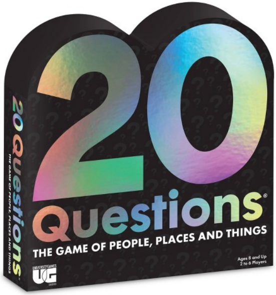
- We propose to leverage the redundancy in the observations and the mechanism of message passing.

Future Work: LTV System Identification



- Consider an LTV environment, sounding pulses are needed for sensing the LTV system (e.g., using the sampling in the Delay-Doppler domain).
- What is the trade-off between sounding the LTV environment and communications over the sounding pulses? Is OTFS good?

Future Work: Cognitive ISAC



- "Radar as a game of 20 questions with an operator" – R. Calderbank
- Cognitive sensing wants to ask questions, adaptively to the answers, and explore unknowns, while communications just want to exploit known good channels. What is the trade-off between exploration and exploitation?

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Related Papers

1. H. Li, “Spectral efficiency in wideband joint communications and sensing: Is OFDM+QPSK (near) optimal?” IEEE International Conference on Communications (ICC), 2024
2. H. Li, Z. Han, and H. V. Poor, “Sphere packing analysis for performance trade-off in joint communications and sensing-Part I: Fourier Analysis of Volume,” IEEE International Conference on Communications (ICC), 2024
3. H. Li, Z. Han, and H. V. Poor, “Sphere packing analysis for performance trade-off in joint communications and sensing-Part I: Generic Principle,” IEEE International Conference on Communications (ICC), 2024
4. H. Li, Z. Han, and H. V. Poor, “ Trellis Waveform Shaping in Joint Communications and Sensing: A Duality to PAPR Mitigation” IEEE International Symposium on Joint Communications and Sensing, 2024
5. H. Li, “ ISAC-Motivated Interference Elimination in Wireless Communication Networks-Part I: Pulse Compression Approach,” IEEE Global Communications Conference, 2023
6. H. Li, “ ISAC-Motivated Interference Elimination in Wireless Communication Networks-Part II: Performance Analysis,” IEEE Global Communications Conference, 2023
7. H. Li, “ Watermarking Based Waveform Synthesis in Joint Communications and Sensing,” IEEE Global Communications Conference, 2023
8. H. Li, “ Whistleblower Joint Communications and Sensing Using Retrodirectional Array Processing,” IEEE Global Communications Conference, Workshop, 2023
9. H. Li, Z. Han and H. V. Poor, “A Broadcast Channel Framework for Joint Communications and Sensing-Part I: Feasible Region,” IEEE Global Communications Conference, 2023
10. H. Li, Z. Han and H. V. Poor, “A Broadcast Channel Framework for Joint Communications and Sensing-Part II: Superposition Coding,” IEEE Global Communications Conference, 2023

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Related Papers (Continued)

1. H. Li, ‘Turbo Bi-static radar in OTFS based joint communications and sensing,” IEEE International Conference on Communications (ICC), 2023.
2. H. Li, ‘Waveform synthesis for MIMO joint communications and sensing with clutters: Part I-Space-time-frequency filtering,” IEEE International Conference on Communications (ICC), 2023.
3. H. Li, “Interference mitigation in joint communications and sensing-Part I: Correlation and collision” IEEE International Symposium on Joint Communications and Sensing, 2023
4. H. Li, “Interference mitigation in joint communications and sensing-Part II: Coding and spreading” IEEE International Symposium on Joint Communications and Sensing, 2023
5. H. Li, “MAC scheduling in joint communications and sensing networks based on virtual queues,” IEEE Global Communications Conference (Globecom), 2022
6. H. Li, “Trade-off in joint communications and sensing with frequency modulation waveforms,” IEEE International Symposium on Joint Communications and Sensing, 2022
7. H. Li, “Unified waveform design in joint communications and sensing with clutter: Shannon or Cramer-Rao?” IEEE International Symposium on Joint Communications and Sensing, 2022
8. H. Li, “Dual-function multiplexing for waveform design in OFDM-based joint communications and sensing,” IEEE International Workshop on Signal Processing for Communications, 2022
9. H. Li, “Interferometry based radar imaging by leveraging cellular communication networks,” IEEE International Workshop on Signal Processing for Communications, 2022

Related Papers (Continued)

1. H. Li, “Performance trade-off in inseparable joint communications and sensing: A Pareto analysis,” IEEE International Conference on Communications (ICC), 2022.
2. H. Li, “Joint communications and sensing using millimeter wave networks: A bonus SAR,” IEEE International Conference on Communications (ICC), 2022.
3. H. Li, “Conflict and trade-off of waveform uncertainty in joint communication and sensing systems,” IEEE International Conference on Communications (ICC), 2022.
4. H. Li, “Degrees of freedom in scattered field for trade-off in joint communications and sensing,” IEEE International Conference on Communications (ICC), 2022.
5. H. Li, “Dirty paper coding in waveform synthesis in integrated communications and sensing: A broadcast channel approach,” IEEE Wireless Communications and Networking Conference (WCNC), 2022.
6. H. Li, “Frequency multiplexing and waveform synthesis of dual functions in joint communications and sensing: Exploitation of mutual benefits,” IEEE International Conference on Communications (ICC), 2022
7. T. N. Guo, H. Li and A. B. MacKenzie, “Efficient and secure spectrum utilization for communication and sensing in UDN by beamspace processing,” IEEE Global Communications Conference (Globecom), 2022

Related Papers (Continued)

1. H. Li, “Dual function trade-off in joint communications and radar: An electromagnetic field analysis,” IEEE Global Communications Conference (Globecom), 2021
2. H. Li, “Inseparable waveform synthesis in joint communications and radar via spatial-frequency frequency,” IEEE Global Communications Conference (Globecom), 2021
3. Y. Fan, J. Bao, K. Wu and H. Li, “Ghost image due to mmWave radar interference: Experiment, mitigation and leverage,” ICC Workshop, 2020.
4. H. Li, “Landscape detection by leveraging millimeter wave communication signals,” IEEE International Conference on Communications, 2019
5. Y. Fan, J. Bao, M. S. Aljumaily and H. Li, “Communication via frequency-modulated continuous-wave radar in millimeter wave band,” IEEE Global Communications Conference, 2019.
6. Z. Zhang, J. Bao and H. Li, “Wind sensing by millimeter wave communications,” IEEE DySPAN, 2019.

Thank You!

Any question?