Integrated Sensing and Communication (ISAC)

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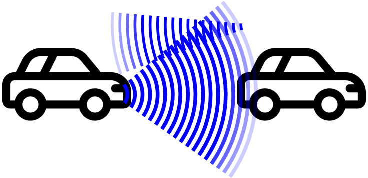
Foundations of Future Networks Workshop

June 19, 2025

Traditional Sensing and Communications Separation

Communication

Sensing

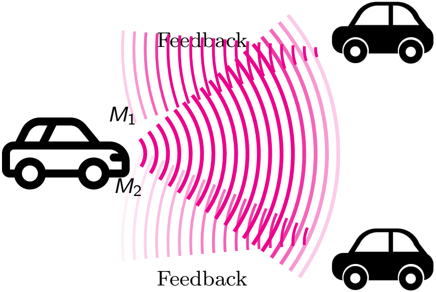


Conventional approach

- Individual hardware with own antenna and own RF chain for each of the two tasks
- Separate bandwidths for the two tasks

Integrated Sensing and Communication (ISAC)

Sensing and Communication



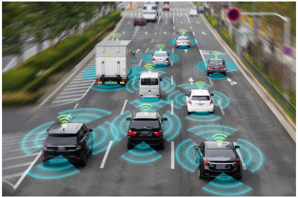
- Synergistic hardware, bandwidth, and waveform performing both tasks: Sensing and Communications

Motivation for Integrating Sensing and Communication

The most immediate benefits of ISAC:

- Cellular communication move up in frequencies, even to the THz regime
  $\rightarrow$ radar and cellular communication occupy similar bandwidths
- Integrating radar and communication will allow to free up precious bandwidth
- Savings in hardware costs, resources, and energy consumption

Important Use Cases



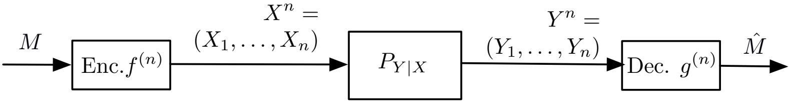
Current Status of ISAC

- Predicted to be crucial building block of future 6G networks
- Heavily investigated in the communications and signal processing societies
- First prototypes available

Information-theoretic angle of attack

Determine the optimal performances of ISAC systems. And the inherent tradeoffs between sensing and communications

The Discrete Memoryless Channel (DMC)



- Discrete-time and stationary memoryless channel law:

$$\mathbb{P}\left[Y_t = y \middle| X^t = x^t, Y_{t-1} = y^{t-1}\right] = P_{Y|X}(y|x_t)$$

- Finite input and output alphabets $\mathcal{X}$ and $\mathcal{Y}$

- Error probability $P_e^{(n)} = \mathbb{P}[\hat{M} \neq M]$

A Refined Shannon Theorem

What Shannon says:

- There is no family of encodings/decodings $\{(f^{(n)}, g^{(n)})\}_{n=1}^{\infty}$ of rate $R > C$
  such that $P_e^{(n)} \to 0$ as $n \to \infty$

- For any rate $R < C$ there does exist a family of encodings/decodings $\{f^{(n)}, g^{(n)})\}_{n=1}^{\infty}$
  s.t. $P_e^{(n)} \to 0$ as $n \to \infty$

A Refined Shannon Theorem

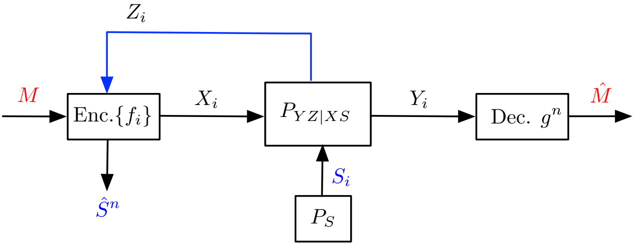
A stronger version:

For any distribution P_X over $\mathcal{X}$:

- There is no family of encodings/decodings $\{(f^{(n)}, g^{(n)})\}_{n=1}^{\infty}$ of rate $R > I(X;Y)$ and with codebook statistics P_X
  such that $P_e^{(n)} \to 0$ as $n \to \infty$

- For any rate $R < I(X;Y)$ there does exist a family of encodings/decodings $\{f^{(n)}, g^{(n)})\}_{n=1}^{\infty}$ with codebook statistics P_X
  s.t. $P_e^{(n)} \to 0$ as $n \to \infty$

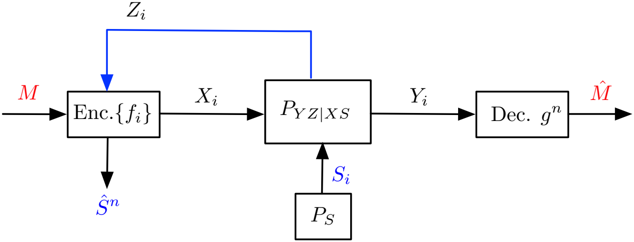
Information Theoretic Model for ISAC Kobayashi et al.



- state sequence $S^n = (S_1, \ldots, S_n)$ i.i.d. $\sim P_S$
- Behaviour of the channel depends on the state S^n (for example the acceleration of an object)
- Sensing Performance measured by Average Block-Distortion:

$$\overline{\lim_{n\to\infty}} \frac{1}{n} \sum_{i=1}^{n} \mathbb{E}[d(S_i, \hat{S}_i)] \le D.$$

Distortion as a Sensing Performance

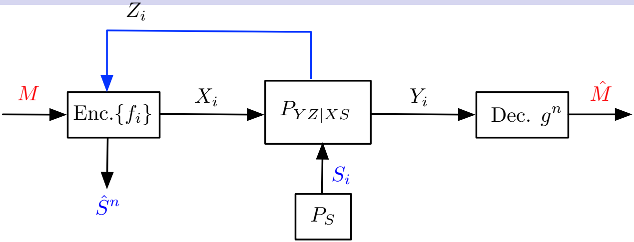


- Sensing Performance Measured by Average Block-Distortion:

$$\overline{\lim_{n\to\infty}} \frac{1}{n} \sum_{i=1}^{n} \mathbb{E}[d(S_i, \hat{S}_i)] \leq D.$$

- Examples of distortion measures
  - Mean-Squared Error $d(s, \hat{s}) = (s - \hat{s})^2$
  - Hamming weight $d(s, \hat{s}) = \mathbb{1}\{s \neq \hat{s}\}$
  - Distortion on a function of the state $d(s, \hat{s}) = d'(f(s), \hat{s})$

Information-Theoretic Fundamental Limit



Definition

Capacity-distortion tradeoff $C(D)$ is largest rate R such that there exist encoders, decoders and estimators with

$$\Pr\left(\hat{M} \neq M\right) \to 0 \quad \text{as} \quad n \to \infty$$

and

$$\varlimsup_{n\to\infty} \frac{1}{n} \sum_{i=1}^{n} \mathbb{E}[d(S_i, \hat{S}_i)] \leq D$$

Capacity-Distortion Tradeoff $C(D)$

Theorem (Kobayashi et al.)

Capacity-distortion tradeoff

$$C(D) := \max I(X; Y)$$

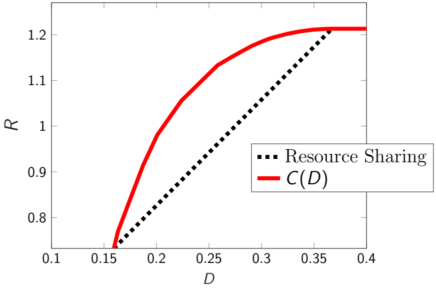
where maximum is over P_X *satisfying*

$$\mathbb{E}[d(S, \hat{s}^*(X, Z))] \leq D.$$

- Tradeoff between communication and sensing stems from P_X
- Generalized feedback not used for coding. Simple point-to-point codes are sufficient. It suffices to adjust input pmf P_X to desired sensing performance.

Ex.: Rayleigh Fading Channel

- Standard Gaussian state and noises S, N, N_{fb}
- Rayleigh fading channel $Y' = SX + N$
- Rx observes $Y = (Y', S)$ and Tx $Z = Y' + N_{\mathrm{fb}}$
- Input power constraint $P = 10dB$
- Quadratic distortion $d(s, \hat{s}) = (s - \hat{s})^2$.



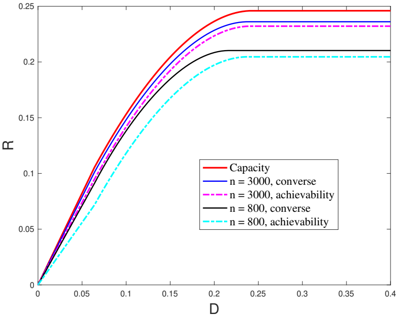
- $X \sim \mathcal{N}(0, P)$ achieves capacity
- $X \pm \sqrt{P}$ optimal for sensing

The Finite Blocklength Regime

- Given blocklength n, triple (R, D, ϵ) is called achievable if $\exists$ encoder, decoder, and estimator with

$$\Pr\left(\hat{M} \neq M\right) \leq \epsilon \qquad \text{and} \qquad \frac{1}{n}\sum_{i=1}^{n} \mathbb{E}[d(S_i, \hat{S}_i)] \leq D$$

- Can reuse the optimal estimator $s^\star(x, z)$ from the capacity-problem!
- Ex.: $Z = Y = XS$ and $S \sim \mathbb{B}(0.4)$ and $\epsilon = 10^{-3}$



[3] H. Nikbakht et al., "Integrated Sensing and Communication in the Finite Blocklength Regime", ISIT 2024.

Information-Theoretic Finite-Blocklength Bounds

Theorem

Given n. *Triple* $(\mathsf{R}, D, \epsilon)$ *is achievable if* $\exists\ P_X$ *and* $\mathsf{K} > 0$ *s.t.:*

$$\mathsf{R} \leq I(X;Y) - \sqrt{\frac{\mathsf{V}}{n}}\mathbb{Q}^{-1}(\epsilon - \beta_u) - \mathsf{K}\frac{\log(n)}{n}, \quad (1)$$

$$D \geq \mathbb{E}[d(S, \hat{s}^\star(X, Z))] \quad (2)$$

with $\beta_u := \frac{1}{n^{\mathsf{K}}} + \frac{0.7975\mathsf{T}}{\sqrt{n\mathsf{V}^3}}$ *and* V / T *the 2nd / 3rd cent. mom. of* $i(X;Y)$.
Triple $(\mathsf{R}, D, \epsilon)$ *not achievable if* $\forall \delta > 0$ *and pmfs* P *satisfying (2):*

$$\mathsf{R} \geq I(X;Y) - \sqrt{\frac{\mathsf{V}}{n}}\mathbb{Q}^{-1}(\epsilon + \beta_l) + \frac{\log(n)}{2n} - \frac{\log\delta}{n}, \quad (3)$$

where $\beta_l := \frac{6\mathsf{T}}{\sqrt{n\mathsf{V}^3}} + \frac{\delta}{\sqrt{n}}$.

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[3] H. Nikbakht et al., "Integrated Sensing and Communication in the Finite Blocklength Regime", ISIT 2024.

Beyond the Memoryless Assumption

- *arbitrary* state sequence $S^n = (S_1, \ldots, S_n)$ (for each n)
- No feedback coding $X^n = f^n(M)$
- *arbitrary* channel law $P_{Z^nY^n|X^nS^n}$ (for each n)
- *general* distortion constraint $\overline{\lim}_{n\to\infty} \frac{1}{n}\mathbb{E}[d(S^n, \hat{S}^n)] \le D$

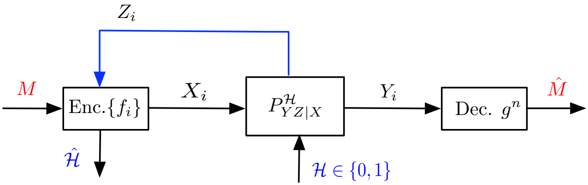
Theorem (Capacity-distortion tradeoff)

$$C(D) := \sup_{\{P_{X^n}\}_n} p-\underline{\lim}_{n\to\infty} \frac{1}{n} i(X^n; Y^n)$$

where supremum over all $\{P_{X^n}\}$ *s.t.* $\overline{\lim}_{n\to\infty} \frac{1}{n}\mathbb{E}[d(S^n, \hat{S}^n(X^n, Z^n))] \le D$

[4] Chen et al. "On general capacity-distortion formulas of integrated sensing and communication," Arxiv 2023.

ISAC Models with Detection Exponents



- Single sensing parameter $\mathcal{H} \in \{0,1\}$ constant for all times
- Sensing performance measured in detection-error exponents
  - Symmetric detection exponent:

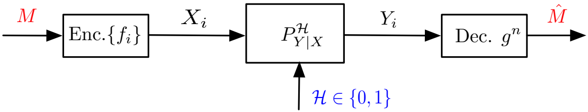
$$E_{\text{Sym}} := \lim_{n\to\infty} -\frac{1}{n} \log \left(\max \left\{ \mathbb{P}\left[\hat{\mathcal{H}} = 1 \mid \mathcal{H} = 0\right], \ \mathbb{P}\left[\hat{\mathcal{H}} = 0 \mid \mathcal{H} = 1\right] \right\} \right)$$

  - Stein's exponent requires

$$\lim_{n\to\infty} \mathbb{P}\left[\hat{\mathcal{H}} = 0 \mid \mathcal{H} = 1\right] \leq \epsilon$$

$$\theta_{\text{Stein}} := \lim_{n\to\infty} -\frac{1}{n} \log \mathbb{P}\left[\hat{\mathcal{H}} = 0 \mid \mathcal{H} = 1\right]$$

Relation to a Compound Channel

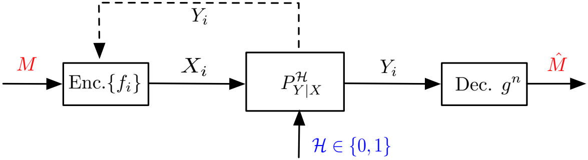


- Without the sensing it is a compound channel
- Compound capacity without feedback:

$$C_{\text{compound}} \leq \max_{P_X} \min_{\mathcal{H}} I(X; Y|\mathcal{H})$$

Cannot adjust codebook statistics P_X to the channel $\mathcal{H}$!

Relation to a Compound Channel



- Without the sensing it is a compound channel
- Compound capacity without feedback:

$$C_{\text{compound}} \leq \max_{P_X} \min_{\mathcal{H}} I(X; Y|\mathcal{H})$$

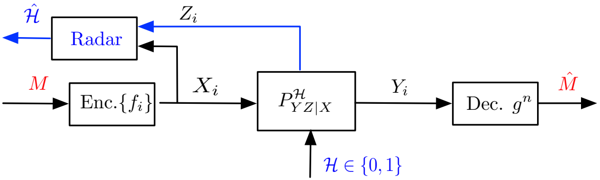
  Cannot adjust codebook statistics P_X to the channel $\mathcal{H}$!

- Compound capacity with feedback:

$$C_{\text{compound,fb}} \leq \min_{\mathcal{H}} \max_{P_X} I(X; Y|\mathcal{H}) = \min_{\mathcal{H}} C(P^{\mathcal{H}}_{Y|X}).$$

  Can learn channel and adapt codebook statistics!

ISAC Model with Stein Error Exponent



Theorem (Ahmadipour et al.)

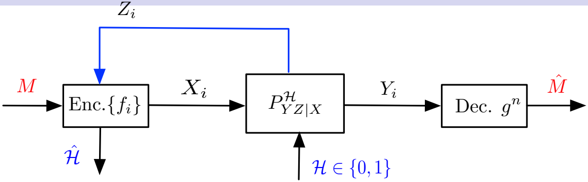
(R, E_{Stein}) *pairs are achievable iff for some* P_X*:*

$$
\begin{aligned}
R &\leq \min_{\mathcal{H}} I(X;Y|\mathcal{H}), \\
E_{\text{Stein}} &\leq \sum_x P_X(x) D(P_{Z|X}(\cdot|x) \| Q_{Z|X}(\cdot|x))
\end{aligned}
$$

- Tradeoff between sensing and communication due to common P_X! (input statistics)

[5] M. Ahmadipour, M. Kobayashi, M. W. and G. Caire, "An Information-Theoretic Approach to Joint Sensing and Communication," *Trans. IT*, 2022.

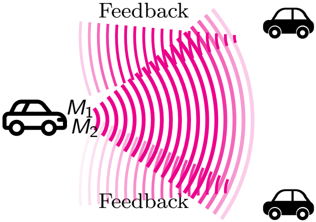
Adaptive Channel Coding/Sensing



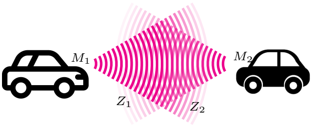
- Feedback allows the encoder to "learn" the channel parameter $\mathcal{H}$ and to adapt its coding to the correct channel
- Sensing (detection) problem is still open when $\mathcal{H}$ non-binary $\rightarrow$ adaptive inputs also improve detection performance
- Chang et al. propose joint sensing and communication schemes
- Problem seems difficult and is open!

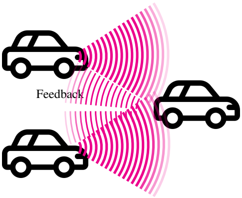
[[7] M.-C. Chang, et al. "Rate and detection-error exponent tradeoff for joint communication and sensing of fixed channel states," *JSAIT 2023*.

Network ISAC



- Data sent to both receivers
- Fundamental limits partly characterized





- Both Transmitters sense and send data
- Comm. path between Txs! → Collaborative comm. and sensing

Summary

- Presented information-theoretic framework for integrated sensing and communication [Kobayashi,Caire,Kramer'18] and [Joudeh&Willems'22]
- Information-theoretic limits have been derived for various sensing criteria and discrete-memoryless channels/state sequences
- Single Tx: optimal sensing performance depends only on x^n statistics.
- Tradeoff between rates and distortion(s)/exponents .
- Multiple Txs: *Fully integrate coding for collaborative sensing and comm.*

Interesting future research directions

- Simplified capacity-expressions/coding schemes for channels with memory
- Continuous-time channels
- Other sensing criteria
- Further investigations on secrecy constraints

IT References on ISAC with Distortion

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- M. Li, O. Simeone, and A. Yener, "Multiple access channels with states causally known at transmitters," *Trans. IT*, 2012.

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