Optimal Time Partitioning in Integrated Sensing and Communication Systems

LINCS Seminar

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Outline

1. Introduction
2. System Model
3. Proposed optimal time partitioning (OTP) framework
4. Performance Evaluation
5. Conclusion

Introduction

- Platooning is a popular driving strategy for autonomous vehicles[1]
    - Platooning ensures line-of-sight communication
    - Useful in traffic planning and developing vehicle-to-vehicle (V2V) infrastructure
    - Equipping the platooned vehicles with object sensing and communication hardware is essential for their smooth movement
- Integrated sensing and communication (ISAC) is emerging as a popular strategy in autonomous V2V systems.

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[1] P. Wang, B. Di, H. Zhang, K. Bian, and L. Song, "Platoon cooperation in cellular V2X networks for 5G and beyond," IEEE Trans. Wireless Commun., vol. 18, no. 8, pp. 3919–3932, 2019.

Motivation

- Object sensing and data communication operations are influenced by multiple design parameters:
    - Transmit power
    - Communication channel gain
    - Range and velocity of target
    - Time duration for sensing and communication
- Aim to quantify the optimality of the sensing and communication time duration
- Analyze the influence of sensing and communication design parameters on the time duration
- Study of coupling between the sensing and communication parameters

Contributions

- Propose an optimal time partitioning (OTP) framework for ISAC systems
- Incorporating and study the tradeoffs among all the sensing and communication design parameters involved.
- Propose a sensing measure to model and quantify the radar sensing performance as a function of maximum detectable range and velocity of the target object.
- Formulate a convex optimal time partitioning problem, wherein the problem is constrained by performance guarantees of both sensing and communication.
- Derive optimal bounds on the sensing and communication time duration, providing insights about the coupling of the performance measures.

System Model

- An ISAC based V2V platooning system wherein a vehicle **A** senses and communicates with another vehicle **B** in the platoon, as illustrated in figure below.

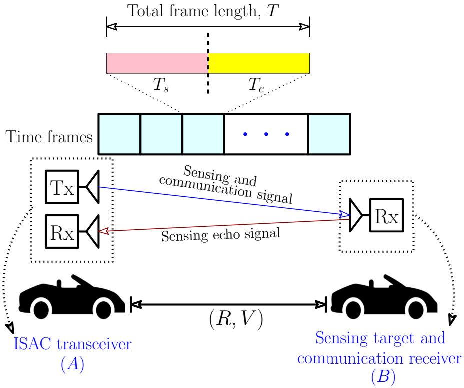

Figure: Illustrating ISAC based V2V system model and timing structure.

- The ISAC system operates in a half duplex fashion: no interference between communication and sensing operations.

System model contd...

- The vehicle **B** is at a distance R and moving with velocity V
- Vehicle **A** has an ISAC transceiver, comprising of a transmitter (Tx) capable of performing object sensing as well as data communication.
- Vehicle **A** transmits an FMCW signal to vehicle **B** at the beginning of each time frame.
- Vehicle **A** senses vehicle **B** through the echo signal captured at the receiver (Rx) of **A**, while data communication occurs at the receiver of vehicle **B**.
- The sensing and communication operations are carried out in a time division multiplexed manner.
- The ISAC system is assumed to have a coherent processing interval (CPI) of duration T, which is partitioned into a sensing duration T_s followed by a communication duration T_c

Sensing Model

Proposition

We define a sensing measure for an FMCW radar as

$$C_S = \log_2\left(1 + \frac{8B_s T_s R_m V_m}{c\lambda}\right). \tag{1}$$

- B_s *denotes the sensing bandwidth,*
- R_m *denotes the maximum sensing range,*
- V_m *represents the maximum detectable velocity by the radar,*
- T_s *denotes the sensing time duration,*
- $\lambda = \frac{c}{f_r}$ *represents the wavelength of the radar having center frequency* f_r*,*
- c *denotes the speed of propagation*

- At the receiver of an FMCW radar, the received signal is de-chirped and sampled with a sampling frequency to obtain range-Doppler matrix for parameter estimation.
- To obtain a sensing measure for radar, each cell in the range-Doppler matrix is assumed to contain a binary value,
  - 1 representing the presence of target
  - 0 indicating an unoccupied cell.
- This assumption allows us to define the maximum capacity of an FMCW radar for one CPI with N chirps as

$$C_S = \log_2(\mathbf{\Gamma}), \tag{2}$$

- $\mathbf{\Gamma} = MN$ is the total number of independent resolution cells in the range-Doppler matrix, with M being the number of range bins and N the number of velocity bins.
- $M = (2R_m B_s/c)$ (maximum range bins)
- $N = (4V_m T_s/\lambda)$ (maximum doppler bins)

- We simplify (1) as $C_S = K \ln(1 + K_s T_s)$, where $K = 1/\ln(2)$ and $K_s = (8 B_s R_m V_m / c\lambda)$.
- The concave nature of the proposed sensing measure for variations in R_m and V_m is shown below

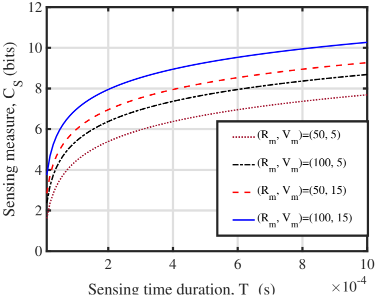

Figure: Illustrating concave nature of the proposed sensing measure w.r.t. R_m (m) and V_m (m/s).

System Model: Communication Model

- Vehicle A is assumed to communicate with vehicle B over a Rayleigh fading channel [2], the corresponding achievable data rate is given as

$$\begin{aligned} R_c &= \frac{B_c}{\ln 2} \ln\left(1 + \frac{|h|^2 P_c^T}{N_0 B_c R^2}\right), \\ &= B_c K \ln(K_c). \end{aligned} \tag{3}$$

- Channel gain is exponentially distributed with unit mean, i.e., $g = |h|^2 \sim \exp(1)$.
- The data rate expression can be further simplified as $R_c = B_c K \ln(K_c)$, with $K = 1/\ln 2$ and $K_c = (1 + gP_c^T/N_0 B_c R^2)$.

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[2] P. Wang, B. Di, H. Zhang, K. Bian, and L. Song, "Platoon cooperation in cellular V2X networks for 5G and beyond," IEEE Trans. Wireless Commun., vol. 18, no. 8, pp. 3919–3932, 2019

Performance guarantees

- To ensure radar sensing performance in terms of false alarm rate and detection probability, the SNR of the received echo of an FMCW radar must be considered.
- For an FMCW radar, echo SNR is defined as

$$SNR_s = \left(\frac{\sigma P_{Ts} G^2 \lambda^2 T_s}{(4\pi)^3 R^4 k T_{temp} B_s} \right), \qquad (4)$$

where

  - σ is radar cross section (RCS) of the target,
  - P_{Ts} is the transmit power of each antenna element of the radar,
  - G is antenna gain (assumed equal for transmit and receive antenna),
  - k is the Boltzmann constant,
  - and T_{temp} is the operating temperature of the radar.

- The optimal radar sensing performance in terms of range and velocity detection, as well as false alarm and detection probability is guaranteed if

$$T_s \geq \left(\frac{SNR_{req}(4\pi)^3 R_m^4 k T_{temp} B_s}{\sigma_{min} P_{Ts} G^2 \lambda^2} \right) = \tau. \tag{5}$$

    - SNR_{req}: the required echo SNR
    - σ_{min}: the minimum RCS requirement

- The communication QoS is guaranteed with respect to the communication throughput achieved through the framework.

$$T_c R_c \geq \alpha, \tag{6}$$

where α denotes the minimum data required to be transmitted in the V2V ISAC framework.

OTP Formulation and Solution

- The OTP formulation by considering the total capacity of sensing, communication and timing constraint to obtain an optimal time allocation strategy is

$$\begin{aligned} P1 : \max_{T_s} \ & K \ln(1 + K_s T_s) \\ s.t., \ C_1 : \ & T_s \geq \tau \\ C_2 : \ & T_c B_c K \ln K_c = (T - T_s) B_c K \ln K_c \geq \alpha, \end{aligned} \tag{7}$$

where $\tau = \left(\frac{SNR_{req} (4\pi)^3 R^4 k T_{temp} B_s}{\sigma P_{T_s} G^2 \lambda^2} \right)$.

Theorem

The optimal sensing and communication time duration, considering the sensing and communication performance guarantees, is given as

$$T_s^* = \begin{cases} \tau, & \text{if } \alpha = (T - \tau) B_c K \ln K_c \\ \left(\frac{T K_s B_c K \ln K_c + B_c K \ln K_c - K_s \alpha}{K_s B_c K \ln K_c} \right) - \frac{1}{K_s}, & \text{if } \alpha < (T - \tau) B_c K \ln K_c, \end{cases} \tag{8}$$

and $T_c^* = T - T_s^*$.

The lagrangian

- The objective function in (7) is observed to be concave while the constraints are affine.
- The Lagrangian of P1 is defined as,

$$\mathcal{L}(T_s,\gamma,\beta)=K\ln(1+K_sT_s)+\gamma(T_s-\tau)+\beta\left((T-T_s)B_cK\ln K_c-\alpha\right). \tag{9}$$

- Solving $\partial\mathcal{L}/\partial T_s=0$, we can obtain

$$\begin{gathered}\frac{KK_s}{1+K_sT_s}+\gamma-\beta B_cK\ln K_c=0\\ \text{resulting in, } T_s=\frac{K}{(\beta B_cK\ln K_c-\gamma)}-\frac{1}{K_s}.\end{gathered} \tag{10}$$

The Dual

- The dual is formed by substituting the primal solution (10) in (9).
- The resulting dual is given as

$$\begin{aligned}\mathcal{G}(\gamma,\beta) = K \ln\left(\frac{KK_s}{\beta B_c K \ln K_c - \gamma}\right) + \frac{\gamma K}{\beta B_c K \ln K_c - \gamma} - \frac{\gamma}{K_s} \\ - \gamma\tau + \beta T B_c K \ln K_c - \frac{\beta B_c K \ln K}{\beta B_c K \ln K_c - \gamma} + \frac{\beta B_c K \ln K_c}{K_s} - \beta\alpha.\end{aligned} \tag{11}$$

- Solving $\partial\mathcal{G}/\partial\gamma = 0$ and substituting in (10), we obtain

$$\begin{gathered}\beta B_c K \ln K_c - \gamma = \frac{KK_s}{1 + K_s\tau}, \\ \text{resulting in, } T_s = \tau.\end{gathered} \tag{12}$$

- Solving $\partial\mathcal{G}/\partial\beta = 0$, and substituting in (10), we get

$$\begin{aligned}\beta B_c K \ln K_c - \gamma &= \frac{B_c K K K_s \ln K_c}{T B_c K K_s \ln K_c + B_c K \ln K_c - K_s\alpha}, \\ \text{resulting in, } T_s &= \left(\frac{T K_s B_c K \ln K_c + B_c K \ln K_c - K_s\alpha}{B_c K K_s \ln K_c}\right) - \frac{1}{K_s}.\end{aligned} \tag{13}$$

Sensing Influence on Communication Rate

- Analyzing the constraints C_1 and C_2 of the primal problem in P1,
  - observe that $T_s \geq \tau$ and $T_s \leq T - \alpha/(B_c K \ln K_c)$.
- Hence the feasible region for optimal T_s is

$$\tau \leq T_s \leq T - \frac{\alpha}{B_c K \ln K_c}. \tag{14}$$

- Using the lower and upper bounds in (14), we obtain

$$\alpha \leq (T - \tau) B_c K \ln K_c. \tag{15}$$

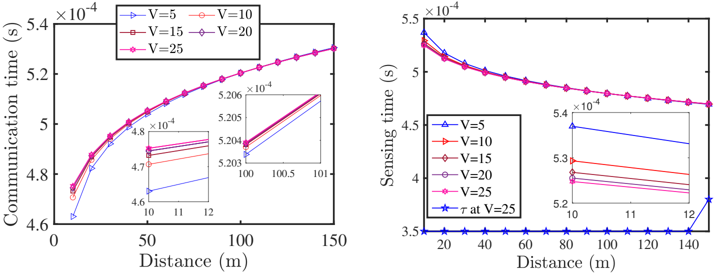
Corollary

The maximum data that can be communicated in a JRC based ISAC system, is a function of the sensing performance guarantee τ in addition to the communication design parameters, i.e., B_c and K_c, and is given by

$$\alpha \leq (T - \tau) B_c K \ln K_c.$$

Performance Evaluation

- The parameters adopted in simulations are: $T = 1$ ms, $P_c^T = 1$ mW, $P_r^T = 15$ mW, $\sigma = 1\ m^2$, $G = 8$ dB, $B_s = 240$ MHz, $B_c = 180$ kHz, $f_r = 77$ GHz, $SNR_{req} = 15$ dB, $\alpha = 1.5 \times 10^3$ bits/frame, $T_{temp} = 300$ K.



(a)

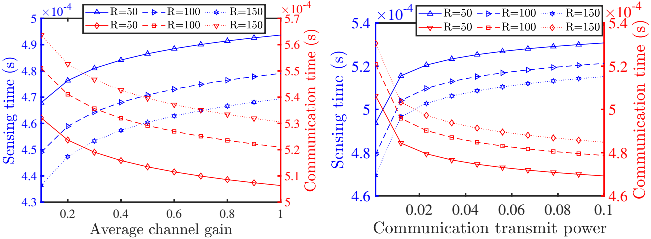
(b)

Figure: Illustration of optimal (a) communication and (b) sensing duration with distance at various velocities (m/s).

- optimal communication time increases with distance, as well as with increasing velocity for a fixed distance, to achieve a given data rate.
- The sensing time reduces adaptively but is greater than the sensing guarantee threshold.

Performance Evaluation

- Optimal sensing and communication duration for varying average channel gain and communication transmit power for various target distances is shown below.



(a) (b)

Figure: variation of sensing and communication time duration with (a) average channel gain (b) communication transmit power.

- observed from Fig. 4(a) that the optimal communication time decreases with increasing average channel gain and increasing transmit power (Fig. 4(b))
- inferred from Fig. 4(b) that the sensing duration decreases with increasing distance, which is consistent with the variation of sensing time shown in Fig. 3(b).

- Communication throughput wrt distance for various channel gains

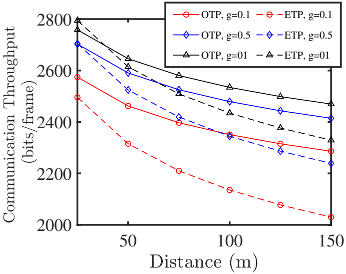


Figure: Comparison of communication throughput variation with distance.

- The proposed OTP framework is compared with an ISAC system considering equal time partitioning (ETP).
- It is observed that with poor channel gain ($g = 0.1,\ 0.5$) the proposed OTP framework achieves a significant gain, up to 12.6%, over the ETP framework.
- for shorter distances $R < 30$ m, throughput with the OTP framework is marginally lower than the ETP framework when $g = 1$.
  - This is because, at shorter distances the optimal communication time computed via the OTP framework to satisfy the QoS is lower – resulting in lower throughput

Conclusion

- Presented an optimal time partitioning (OTP) framework for V2V ISAC systems.
- Proposed a novel radar sensing measure as a function of maximum detectable range and velocity.
- Constrained by sensing and communication performance guarantees, the OTP framework has derived the optimal duration for sensing and communication.
- Provided insight into the maximum achievable communication throughput as a function of sensing guarantee.

Thank You

Questions, Suggestions?

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