System level synchronization of phase-coded FMCW automotive radars for RadCom

DOI:
10.23919/EuCAP48036.2020.9135417

Document status and date:
Published: 08/07/2020

Document Version:
Accepted manuscript including changes made at the peer-review stage

System Level Synchronization of Phase-Coded FMCW Automotive Radars for RadCom

Franz Lampel[1], Faruk Uysal[2], Firat Tigrek[3], Simone Orru, Alex Alvarado[4], Frans Willems[5], Alexander Yarovoy[6]

{[1]f.lampel,[3]r.f.tigrek,[4]a.alvarado,[5]f.m.j.willems}@tue.nl
{[2]f.uysal,[6]a.yarovoy,}@tudelft.nl

Information and Communication Theory Lab,
Signal Processing Systems Group,
Department of Electrical Engineering,
Eindhoven University of Technology, The Netherlands

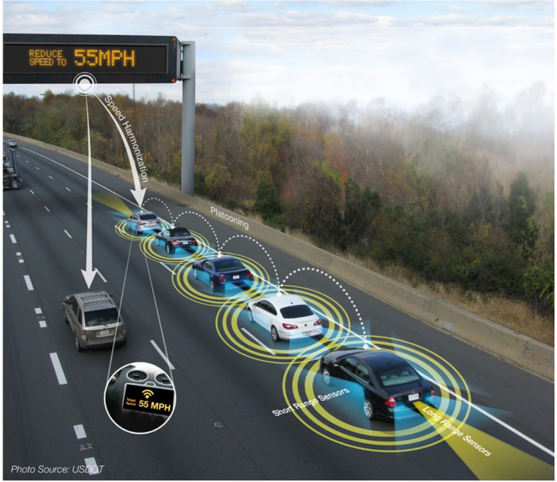
http://www.tue.nl/ictlab

Acknowledgment

This research is supported by the Dutch Technology Foundation TTW which is part of the Netherlands Organisation for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs.

Motivation

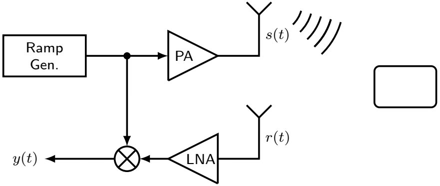
- Autonomously driving vehicles
  - Information exchange
  - V2V communication: spectral congestion
- Embed communication in automotive radar
  - Directional links
  - Mitigate spectral congestion

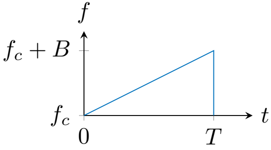


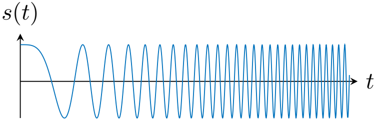
Automotive Radar

- Digitally Modulated Radars:
  - \+ Waveform flexibility
  - \+ Communication capability
  - – Full-band sampling
  - – PAPR
- FMCW:
  - \+ Constant envelope
  - \+ Modest sampling requirements
  - – Limited communication capability

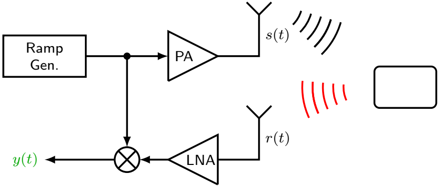
FMCW Radar

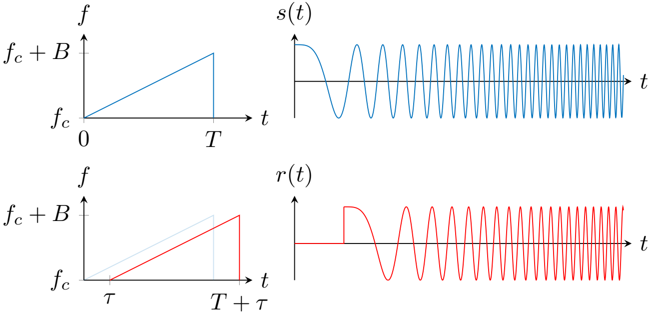




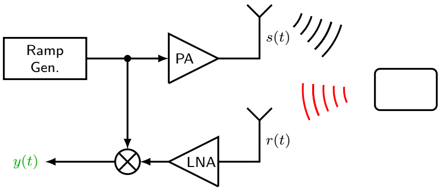


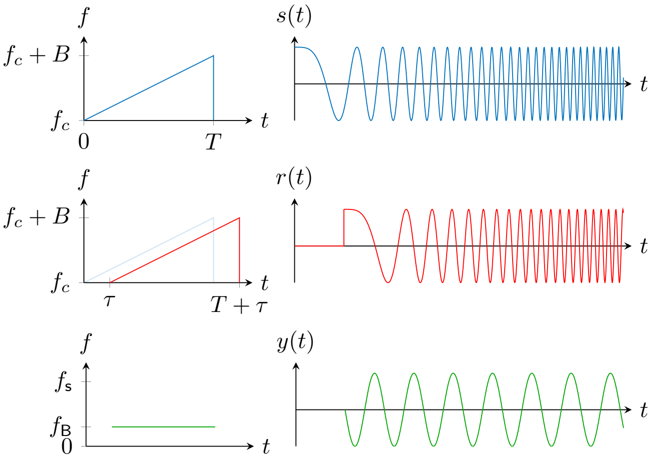
FMCW Radar





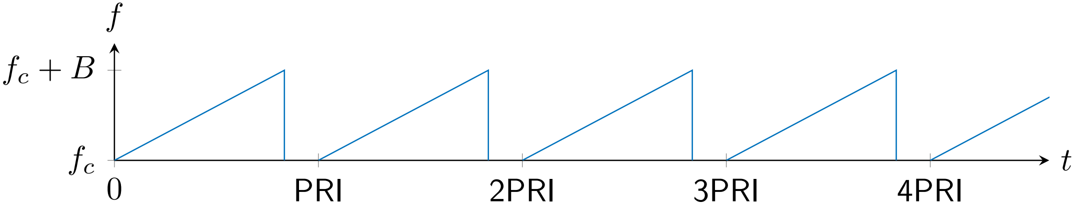
FMCW Radar



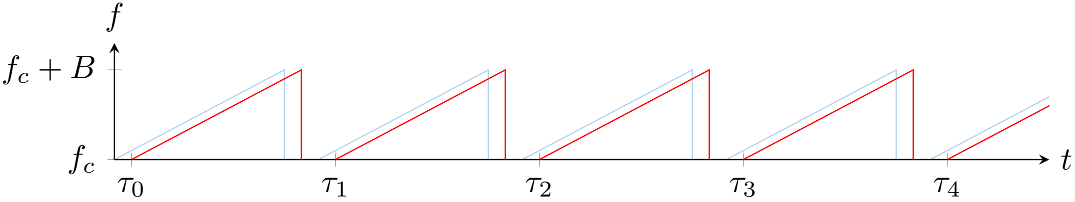


$$f_B = \frac{B}{T} \cdot \tau \qquad (1)$$

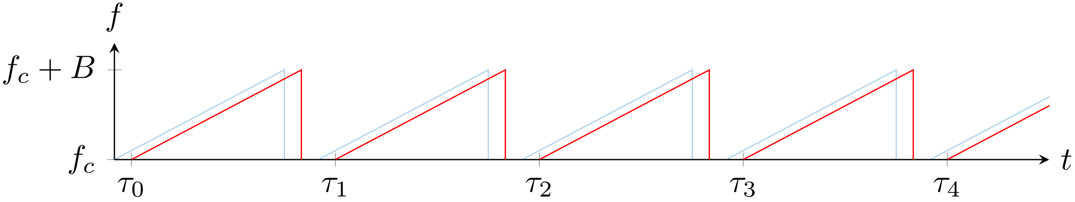
FMCW Chirp Sequence



FMCW Chirp Sequence

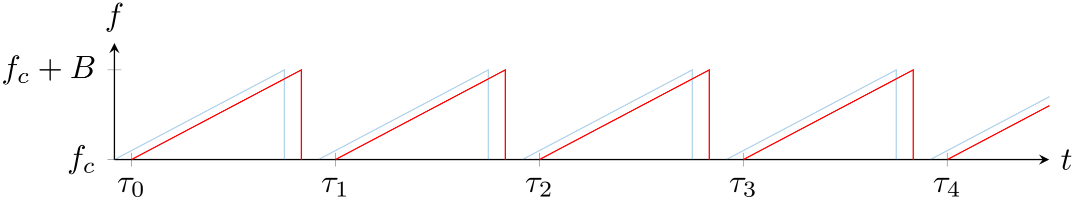


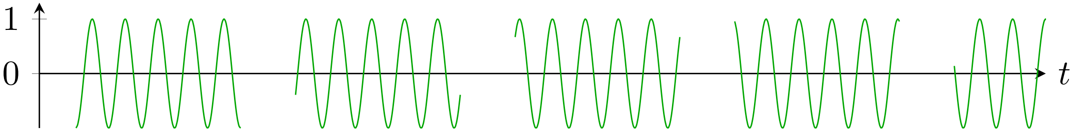
FMCW Chirp Sequence



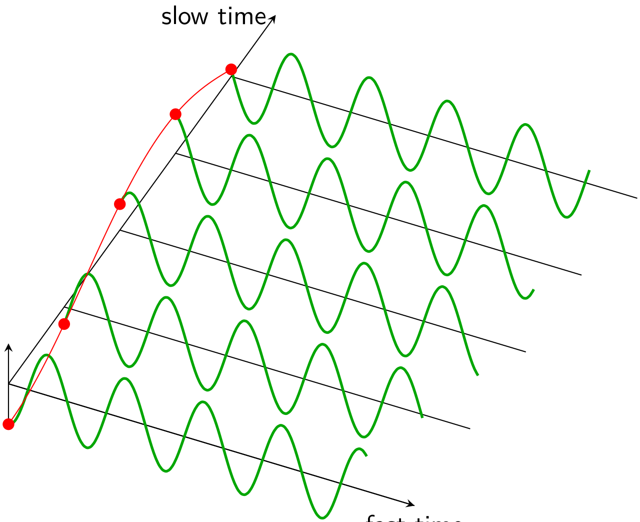
$$\tau_0 < \tau_1 < \tau_2 < \tau_3 < \tau_4 \dots \quad (2)$$

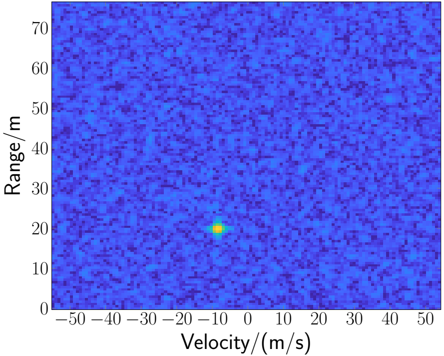
FMCW Chirp Sequence





FMCW Doppler Processing

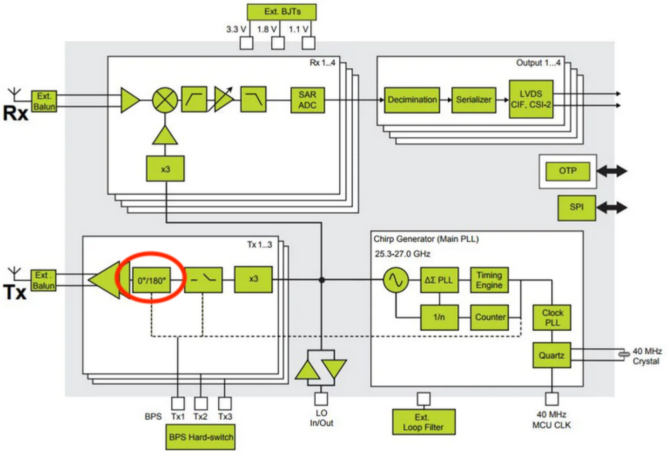




FMCW Transceiver

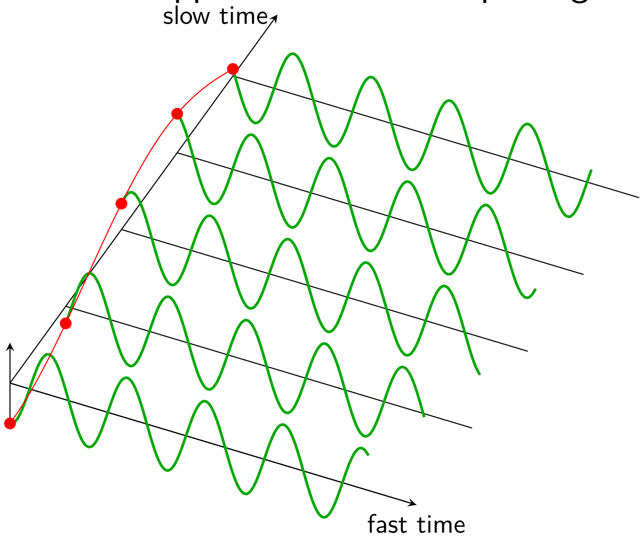
- Angle of Arrival estimation:
  - MIMO
  - Simultaneous transmission
  - Doppler Division
  - Change of consecutive chirps

TEF810X BLOCK DIAGRAM

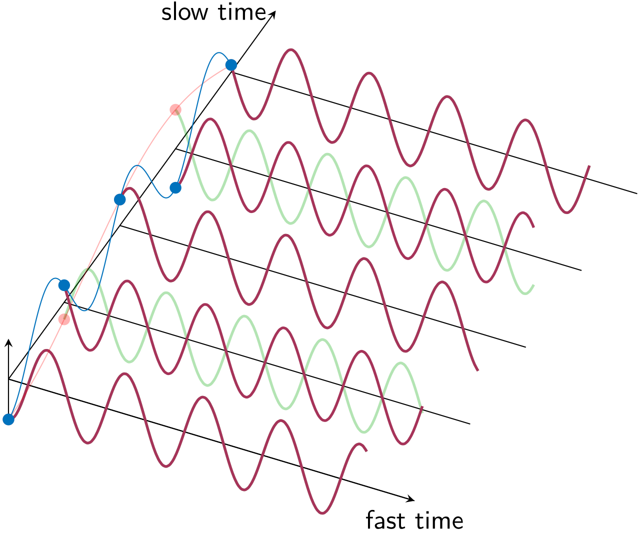


Source: www.nxp.com/products/rf/radar-transceivers/tef810x-fully-integrated-77-ghz-radar-transceiver:TEF810X

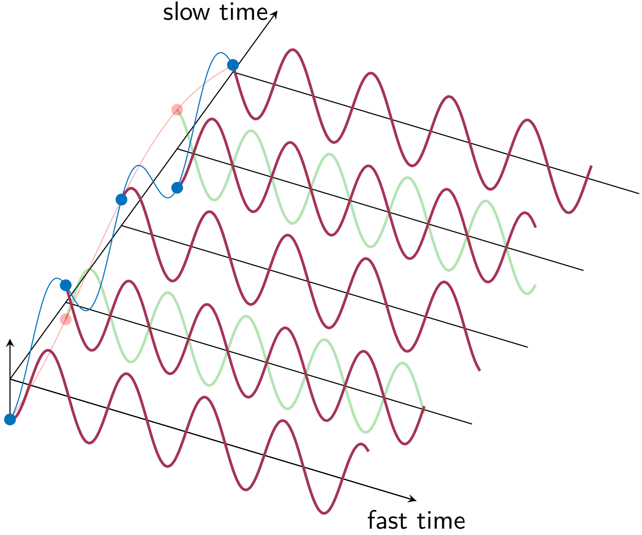
MIMO - Doppler Division Multiplexing

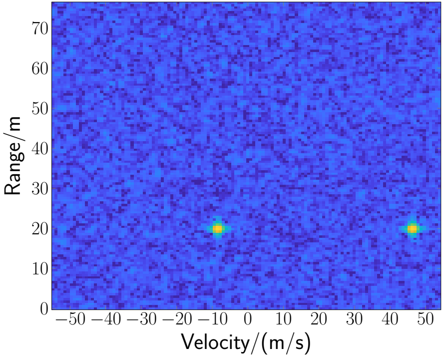


MIMO - Doppler Division Multiplexing



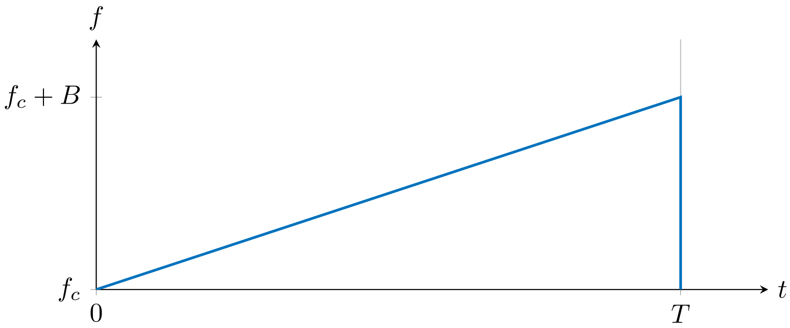
MIMO - Doppler Division Multiplexing





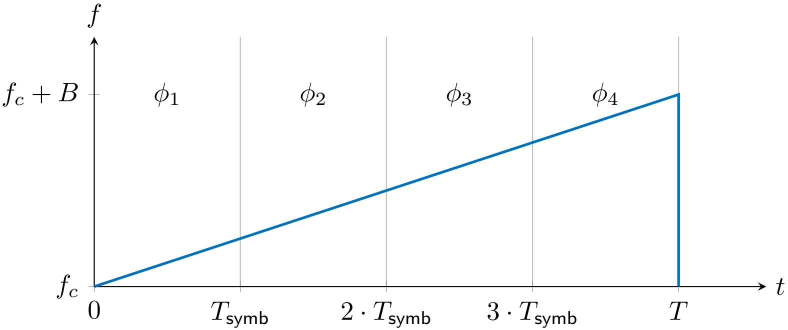
Embedded Communication

- Switch phase multiple times per chirp:
  - **Embedded communication**
  - Interference avoidance
  - Phase coded MIMO



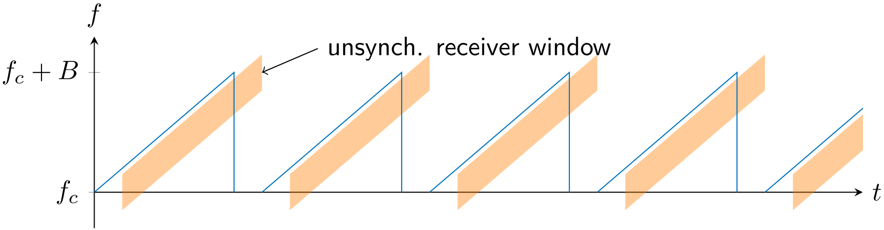
Embedded Communication

- Switch phase multiple times per chirp:
  - **Embedded communication**
  - Interference avoidance
  - Phase coded MIMO



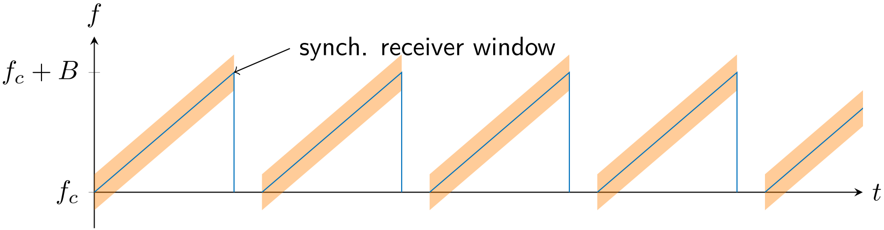
Synchronization

- Chirp: Saw-tooth carrier
- Intermediate frequency must be smaller than maximum frequency
  - Receiver must be synchronized on a chirp level



Synchronization

- Chirp: Saw-tooth carrier
- Intermediate frequency must be smaller than maximum frequency
  - Receiver must be synchronized on a chirp level



Synchronization - Reference Signal

- NXP TEF810X radar module
- Reference: Pulse Per Second (PPS) signal of external GPS module
- 4 bits per chirp

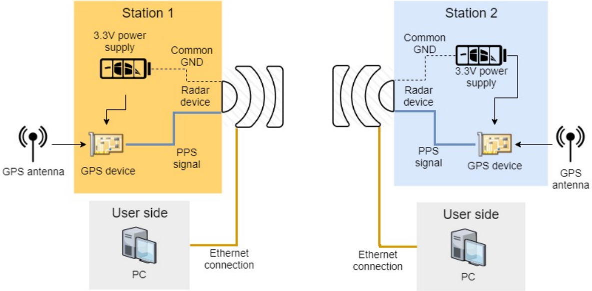


Figure: Test setup

Received Signal

- Phase change visible in baseband signal
- Use second derivative of phase to detect phase change

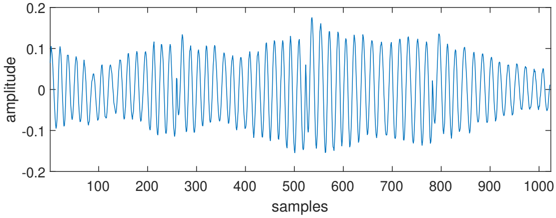


Figure: Received baseband signal

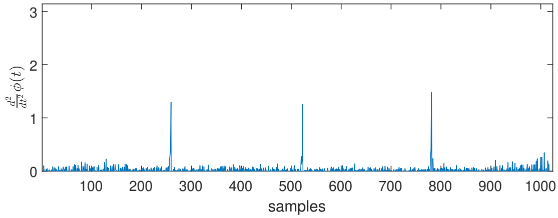


Figure: Second derivative of received phase

Practical Issues

- Accuracy of GPS clock as well as PPS signal
- Accuracy of internal clocks of radar microcontroller unit (MCU) which controls the timing of phase changes during transmission
- Speed of the platforms
- Time of flight between the transmitter and the receiver.

Synchronization Error

- Synchronization error can be estimated and corrected

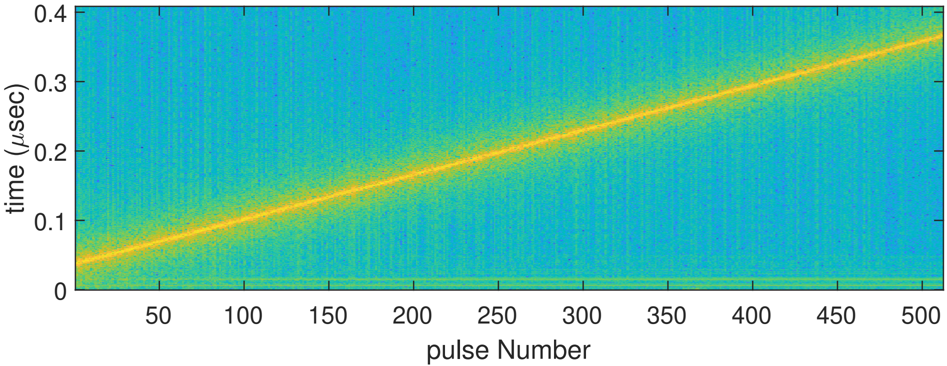
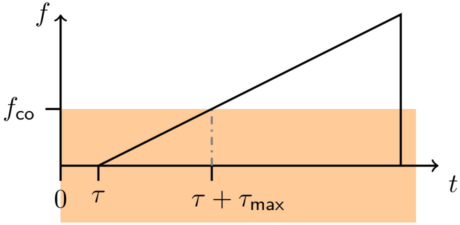


Figure: Evolution of the synchronization error

Synchronization - Chirp Detection

- Receiver demodulates with constant frequency
- Observer chirp partially
- Collect $N = \lfloor \tau_{\text{max}} \cdot f_{\text{s}} \rfloor$ per chirp



Signal Detection

- Chirp signal detectors:
  - Energy detector
  - Matched filter
- Binary hypothesis testing:

$$\mathcal{H}_0 : u[n] = \nu[n], \qquad \text{noise only} \tag{3}$$

$$\mathcal{H}_1 : u[n] = y[n] + \nu[n], \qquad \text{signal plus noise.} \tag{4}$$

$$y[n] = \sqrt{\frac{E}{N}} \exp\left\{ j \left(\pi\alpha \left(\frac{n}{f_\mathrm{s}} \right)^2 - \Theta \right) \right\}, \tag{5}$$

Energy Detector - Output Statistics

- Output

$$r = \sum_{n=1}^{N} |u[n]|^2 \tag{6}$$

- $\mathcal{H}_0$:

$$p_R(r|\mathcal{H}_0) = \begin{cases} \dfrac{r^{N_\mathsf{f}/2-1}}{\sigma^{N_\mathsf{f}} 2^{N_\mathsf{f}/2} \Gamma(N_\mathsf{f}/2)} \exp\left(-\dfrac{r}{2\sigma_i^2}\right), & r > 0 \\ 0, & r \leq 0, \end{cases} \tag{7}$$

- $\mathcal{H}_1$:

$$p_R(r|\mathcal{H}_1) = \begin{cases} \dfrac{1}{2\sigma_i^2} \left(\dfrac{r}{s^2}\right)^{\frac{(N_\mathsf{f}-2)}{4}} \exp\left(-\dfrac{s^2+r}{2\sigma_i^2}\right) & \\ \cdot I_{\frac{N_\mathsf{f}}{2}-1}\left(\sqrt{r}\dfrac{s}{\sigma_i^2}\right), & r > 0 \\ 0, & r \leq 0, \end{cases} \tag{8}$$

Matched Filter - Output Statistics

- Output

$$z = u[n] * h[n] \tag{9}$$

- Phase unknown

$$r = |z|^2 \tag{10}$$

- $\mathcal{H}_0$:

$$p_R(r|\mathcal{H}_0) = \begin{cases} \lambda \exp(-\lambda \cdot r), & r \geq 0 \\ 0, & r < 0. \end{cases} \tag{11}$$

- $\mathcal{H}_1$:

$$p_R(r|\mathcal{H}_1) = \begin{cases} \frac{1}{2\sigma_i^2}\left(\frac{r}{s^2}\right)^{\frac{(N_\mathrm{f}-2)}{4}} \exp\left(-\frac{s^2+r}{2\sigma_i^2}\right) \\ \cdot I_{\frac{N_\mathrm{f}}{2}-1}\left(\sqrt{r}\frac{s}{\sigma_i^2}\right), & r > 0 \\ 0, & r \leq 0, \end{cases} \tag{12}$$

Detector - Performance

- Threshold η

$$r \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} \eta. \tag{13}$$

- False alarm probability:

$$P_{\mathsf{fa}}(\eta) = \begin{cases} \exp\left(\frac{-\eta}{2\sigma_i^2}\right) \sum_{k=0}^{N-1} \frac{1}{k!} \left(\frac{\eta}{2\sigma_i^2}\right)^2, & \text{Energy Detector} \\ \exp\left(-\frac{\eta}{2\sigma_i^2}\right), & \text{Matched Filter.} \end{cases} \tag{14}$$

- Probability of detection:

$$P_{\mathsf{d}}(\eta) = Q_N\left(\frac{s}{\sigma_i}, \frac{\sqrt{\eta}}{\sigma_i}\right). \tag{15}$$

  - Energy detectors: $2N$ degrees of freedom
  - Matched filter: 2 degrees of freedom

Probability of detection

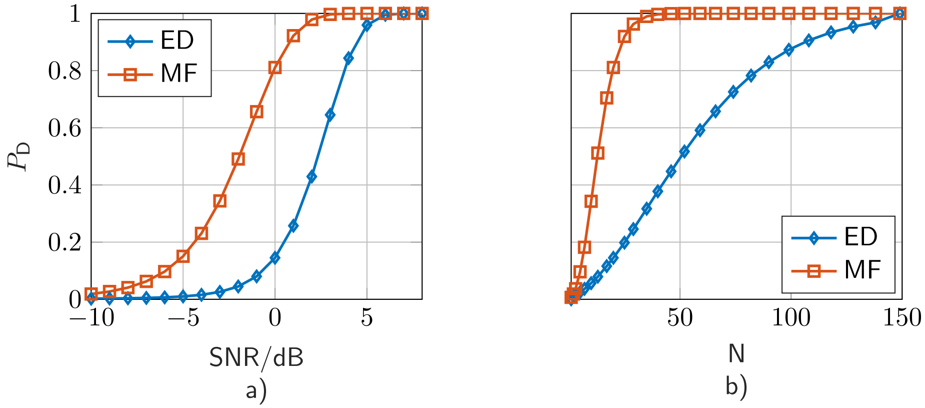


Figure: Probability of detection P_D as a function of the SNR a) and number of samples b). In both examples, η was chosen to target a P_{fa} of 0.001. For a), N was set to 20 while in b) the SNR was fixed to 0 dB.

Conclusion

Take-Home Message

An FMCW radar can be used to embed communication signal into the chirp. It is possible to receive and decode the joint radar signal from another radar. Synchronization can be done by an external reference or by signal detection methods.