3D Sensing for vehicle technologies

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Outline

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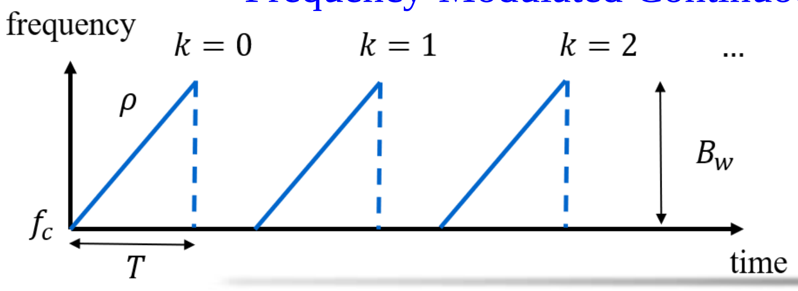
Introduction

- **Why radar?**
  - It's under-researched
  - There is no dominant product or company in the market yet
  - It has some irreplaceable advantages
    - Long detection range (up to 300 m)
    - All-weather operation
    - Low power consumption
    - Most importantly, low cost
- **What radar? Specifically?**
  - FMCW radar means an antenna system that transmits and receives EM waves with certain modulation to achieve certain task
    - Frequency-Modulated Continuous-Wave, FMCW



Technology

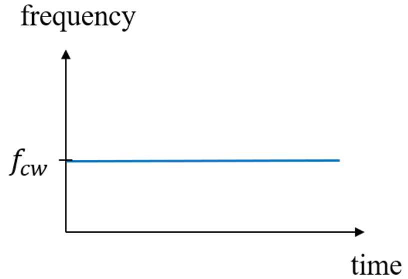
- **FMCW radar fundamentals**
  - Off-the-shelf automotive radars operate with a sequence of **linear FMCW signals** to simultaneously measure **range**, **angle**, and **velocity**
  - The automotive radar is allowed to use **2** frequency bands in mmwaves
    - 24 GHz (24~24.25 GHz)
    - 77 GHz (77~79 GHz)
  - There is a trend towards **77 GHz** for several reasons:
    - **Larger bandwidth**
      - 76–77 GHz for long-range
      - 77–81 GHz for short-range
    - **Higher** Doppler **resolution**
    - **Smaller antennas** with sub-wavelength sized
  - Different radar devices vary in their sensing capabilities
    - Different radar device normally means different **modulation patterns**

Technology

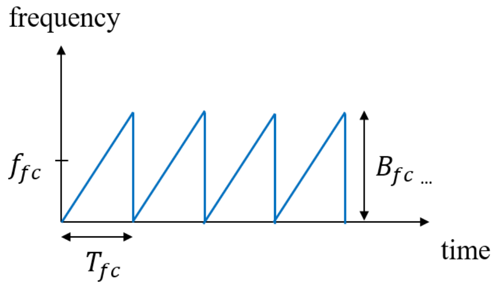
- **Fun facts about frequency bands**
  - Licensed-band in 5G Spec
    - FR1 410 MHz – 7.125 GHz
    - FR2-1 24.25 GHz – 52.6 GHz
    - FR2-2 52.6 GHz – 71 GHz
  - Up to 100 GHz belongs to 5G, but above 71 GHz are not licensed
    - Up to 6 GHz belongs to 4G
  - Aside from licensed-bands, there are also **private 5G (Local 5G)** bands, the specific regulations different from country to country
    - e.g. 4.6 GHz – 4.9 GHz is a private 5G band in Japan
  - How expensive are the frequency bands in 5G in Taiwan?
    - A 15 year authorization cost $150 billion NTD
    - 1 MHz bandwidth worth $200 ~ 500 million NTD

Technology

- **Modulation patterns**
  - Unmodulated CW
    - This modulation pattern is used for some mmwave communication signals

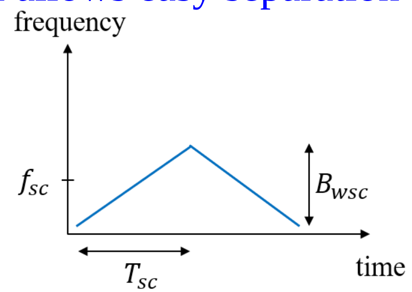


  - Fast chirp FMCW (Sawtooth modulation)
    - This modulation pattern is used in a relatively large range (maximum distance) combined with a negligible influence of Doppler frequency (for example, a maritime navigation radar).
      - Account for 90% of the modulation we probably going to seen in out daily lives

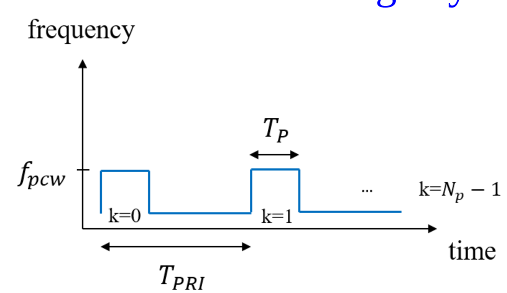


Technology

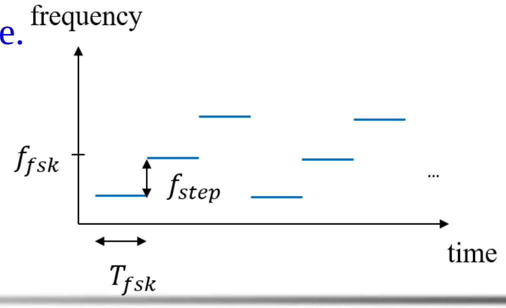
- **Modulation patterns**
  - Slow chirp FMCW (Triangular modulation)
    - This modulation pattern allows easy separation of the difference frequency Δf of the Doppler frequency f_D



  - Pulsed CW (Square-wave modulation)
    - This modulation is used for a very precise distance measurement at close range by phase comparison of the two echo signal frequencies.



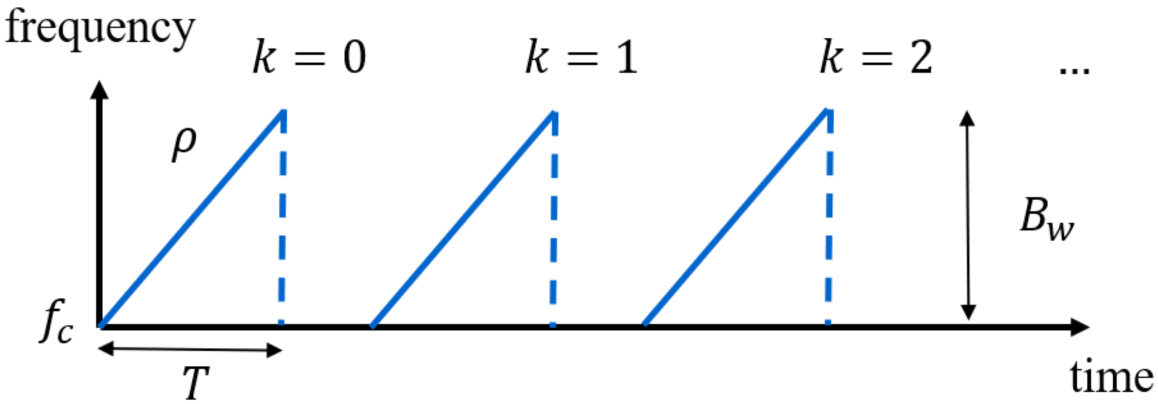
  - FSK (Stepped modulation)
    - This is used for interferometric measurements and expands the unambiguous measuring range.



Technology

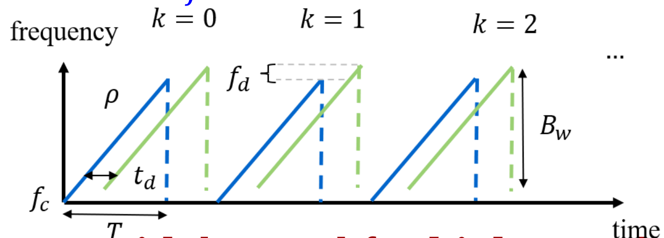
- **FMCW signal is characterized by the following parameters**
  - the **carrier frequency** f_c
  - the **sweep bandwidth** B_w
  - the **chirp duration** T
  - the **slope** $\rho = B_w \,/\, T$
- **FMCW waveform**

$$s_T(t,k) = A_T exp\left(j2\pi\left(f_c t + \frac{\rho}{2}t^2\right)\right) \quad k = 0,1, \ldots K-1, 0 \le t < T$$

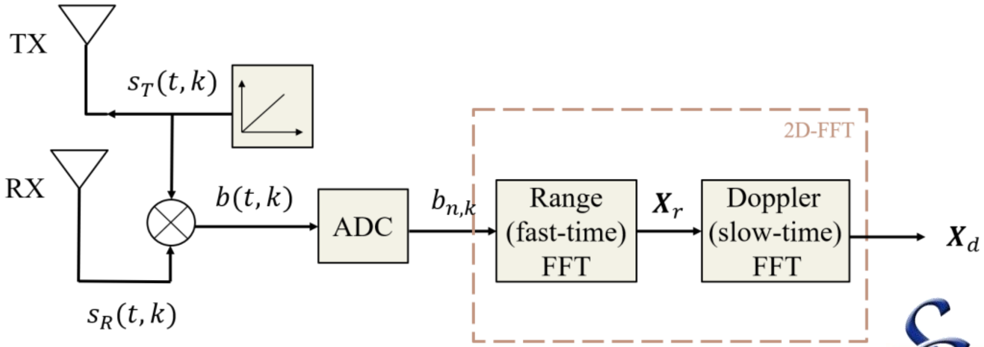


Technology

- **FMCW waveform**
  - **One** FMCW **waveform** is referred to as **a chirp**
  - **One** radar **transmission** is **a frame of** K **chirps** equally spaced by chirp cycle time T
    - The total time $T_f = K \cdot T$ is called **frame time** (time on target, TOT)



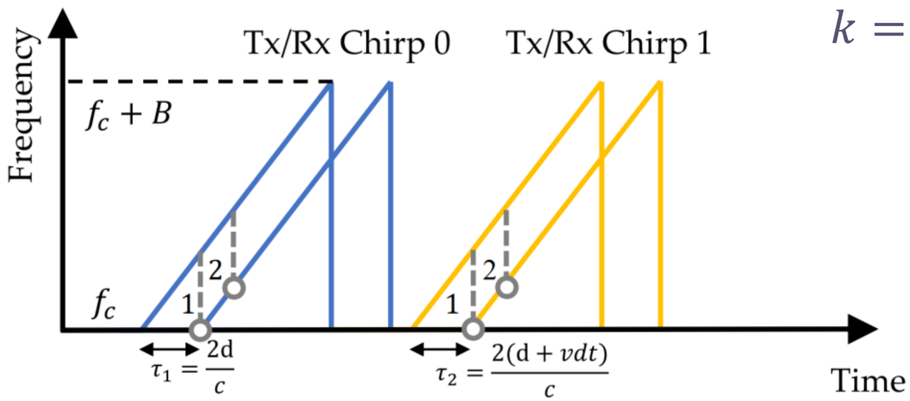
  - In order to **avoid** the need for **high-speed sampling**, a frequency **mixer** combines the received signal with the transmitted signal to produce two signals
    - sum frequency
    - difference frequency



Technology

- **FMCW waveform**
  - Then, a low-pass filter is used to filter out the sum frequency component and obtain the **IF signal** (Intermediate Frequency, IF)
    - In this way, FMCW radar can achieve GHz with only MHz sampling
  - Resulting complex exponential IF signal
  - Next, the IF signal is sampled N times by an ADC converter, resulting in a discrete-time complex signal

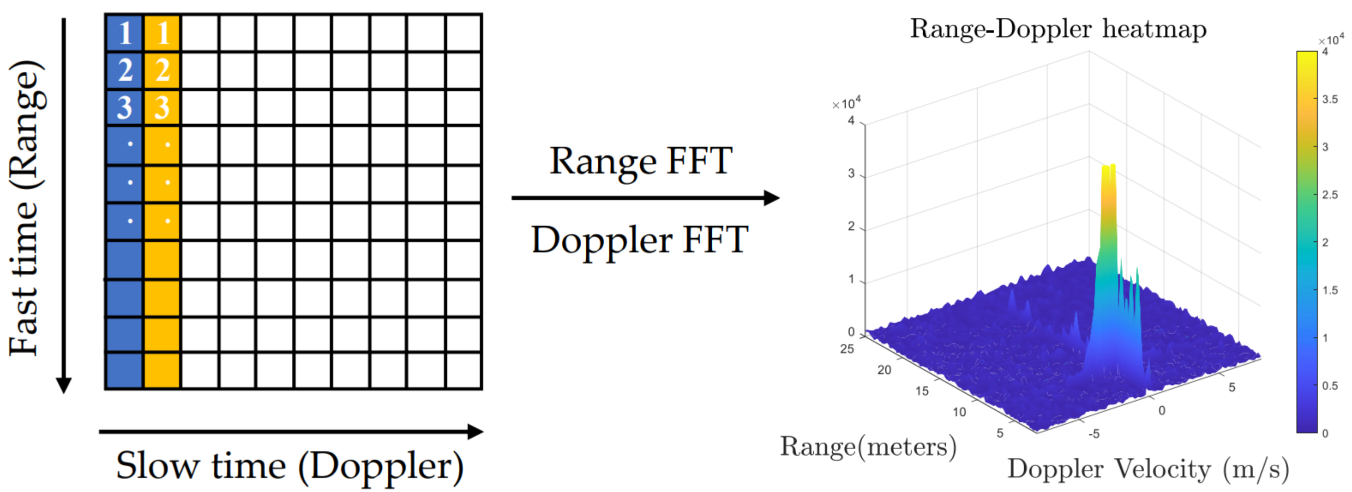
$$s_R(t,k) = A_R exp\left(j2\pi\left((f_c - f_d)(t - t_d) + \frac{\rho}{2}(t - t_d)^2\right)\right)$$



$$k = 0,1, \ldots K - 1, t_d \leq t < T + t_d$$

Technology

- **FMCW signal processing**
  - Multiple frames of chirp signals are assembled into a 2D matrix
    - The dimension of the **sampling points within a chirp** is referred to as **fast time**
    - The dimension of the **chirp index within one frame** is referred to as **slow time**
  - Next, a **range FFT** is applied in the fast-time dimension to resolve the frequency change, followed by a **Doppler FFT** in the slow-time dimension to resolve the phase change.
    - As a result, we obtain a **2D complex-valued data matrix** called the Range–Doppler map, **RD map**

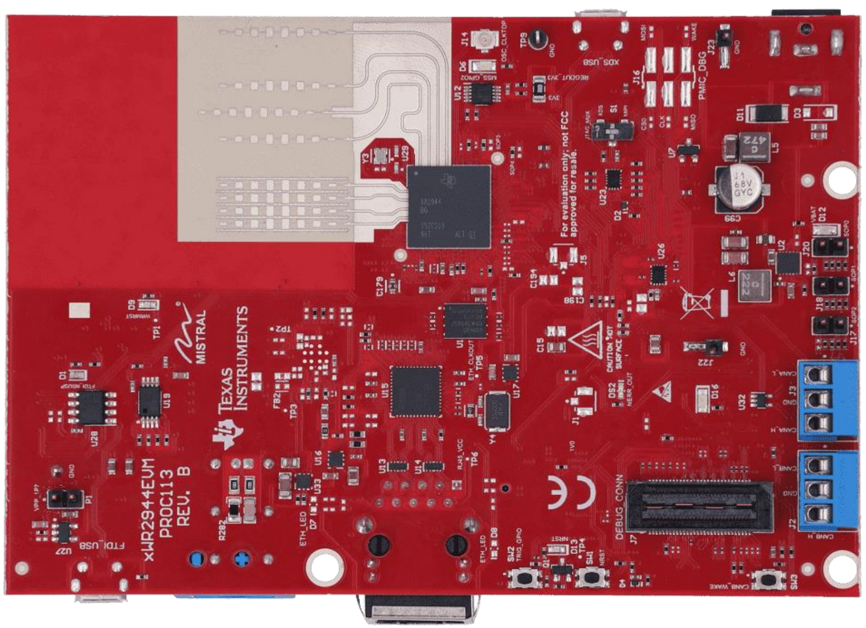


Technology

- **FMCW radar detection pipeline**
  - First, RD maps are integrated coherently along the **virtual receiver dimension** to increase the SNR
    - e.g. say, we have a simple MIMO radar system with 4 Tx and 4 Rx antenna, which means we can synthesize a virtual array with 4 x 4 = 16 channels
  - Then, a CFAR detector is applied to **detect peaks** or **estimate the noise level** in the RD map
  - Finally, the **DOA estimation** method is applied for angle estimation
    - for conventional radars, only **azimuth angle** is resolved
    - for next-generation radars, both azimuth and **elevation angles** can be resolved
  - The output of the radar is a **point cloud** with measurements of range, Doppler, and angle

TI AWR2944EVM

- **Features**
  - 76 to 81 GHz mmwave radar sensor
  - Onboard four-transmit four-receive (**4Tx / 4Rx**) antenna
  - On-chip **C66x DSP** core and **Arm Cortex-R5F** controller
  - On-chip **hardware accelerator** for FFT
- **AWR2944 Evaluation Module (EVM) ($549 USD)**



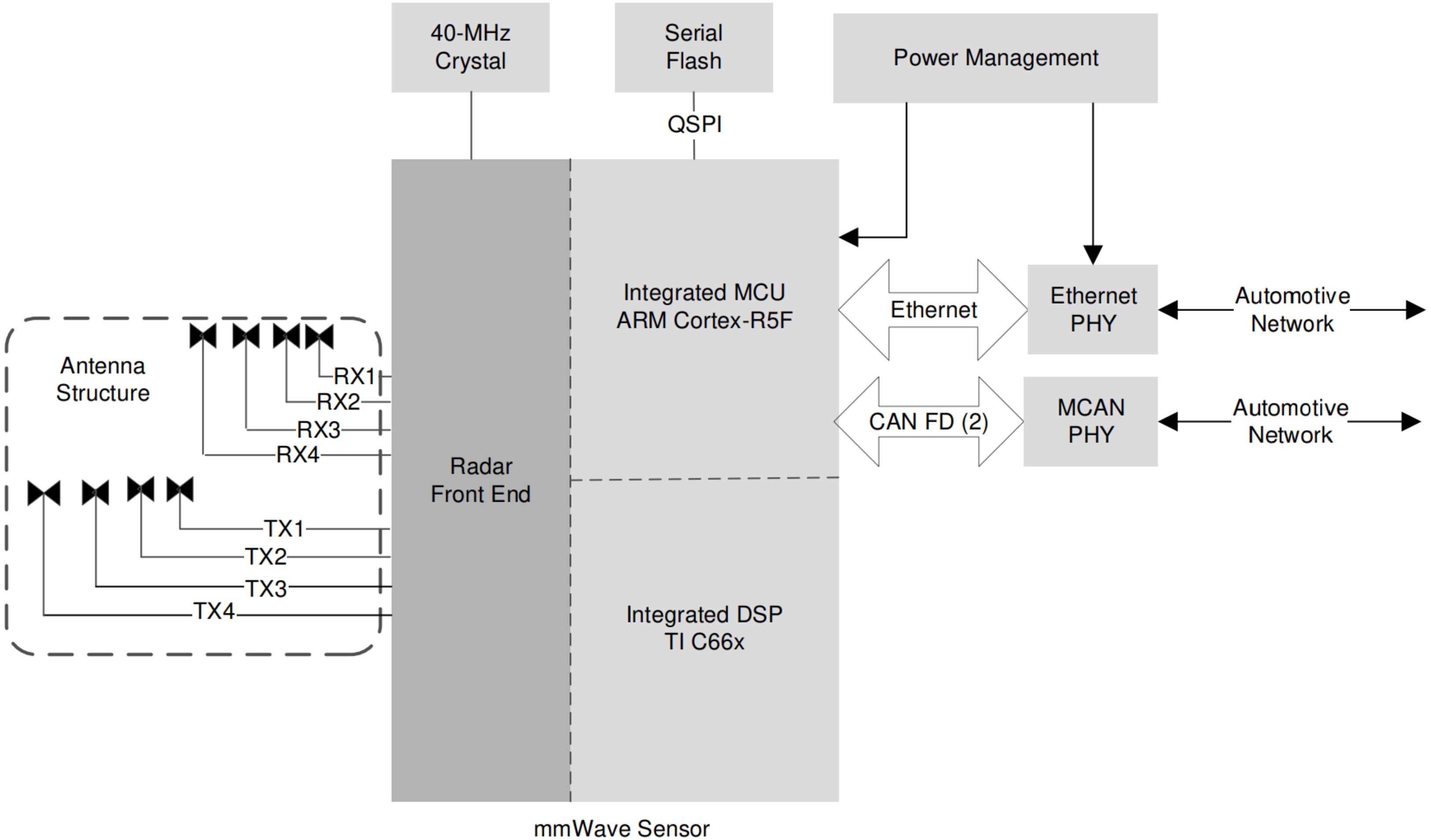
TI AWR2944 Spec

Parameters

Number of receivers	4
Number of transmitters	3, 4
ADC sampling rate (Max) (MSPS)	37.5
Interface type	2 CAN-FD, Ethernet, I2C
DSP	C66x DSP 360MHz
Hardware accelerators	Radar hardware accelerator
Rating	Automotive
Operating temperature range (C)	-40 to 140
Power supply solution	LP87745-Q1
Security	Cryptographic acceleration, Device identity/keys, Secure boot, Secure software update, Software IP protection, Trusted execution environment

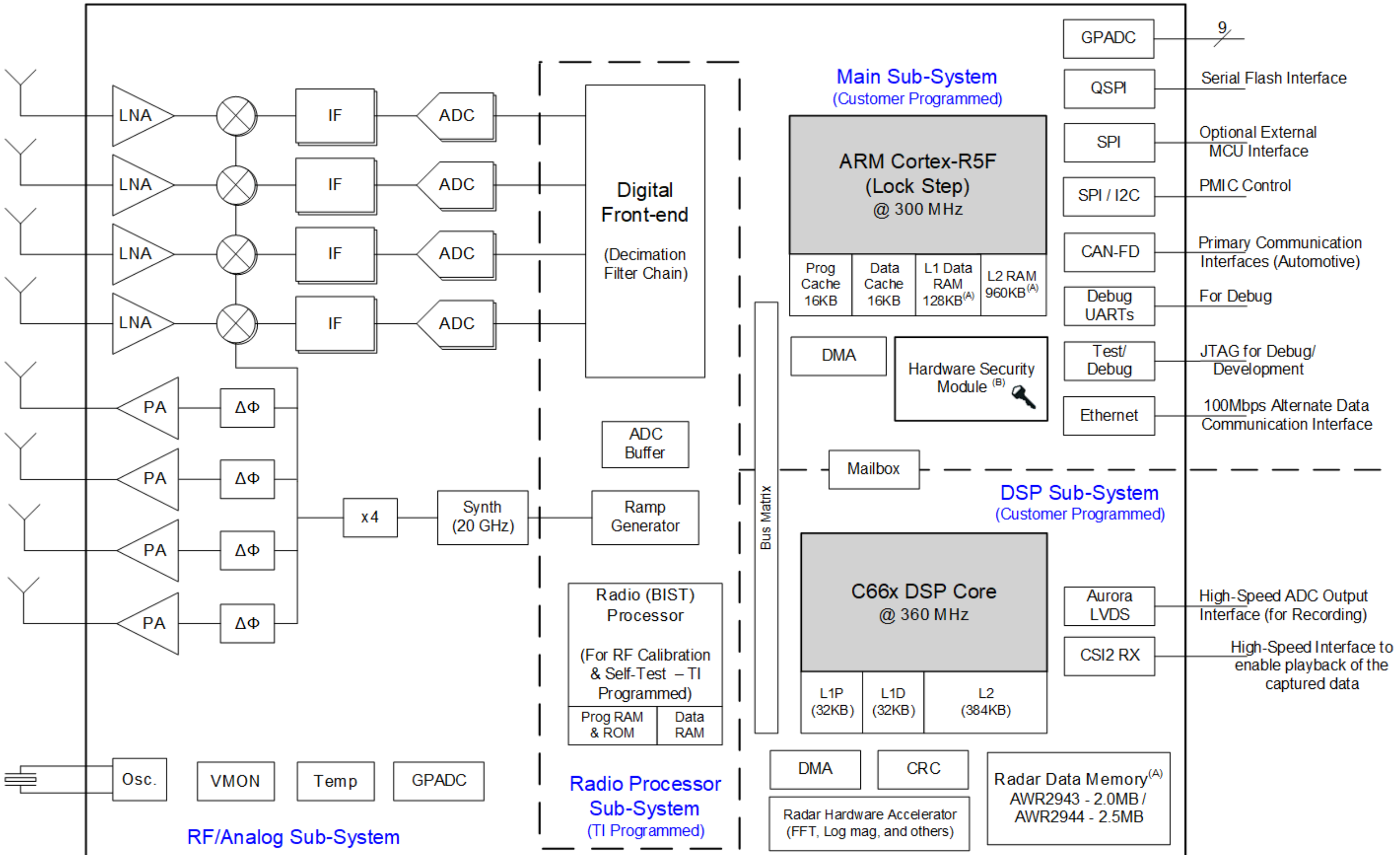
TI AWR2944 Spec

■ Functional Block Diagram



TI AWR 2944 Spec

- **Functional Block Diagram**



Applications

- **Active safety functions**
  - Automatic Emergency Braking (**AEB**)
  - Forward Collision Warning (**FCW**)
- **Autonomous driving**
  - Provide range and velocity estimation for the decision fusion algorithm
- **Non-contact vital sign detection**
  - Breath rate
  - Heart rate
    - Use cases
      - Burn patients
      - Patients that have been isolated due to infectious disease

Opponents

- **Vision – Comma ai Driver Assistance System ($2499 USD)**
  - Camera
    - Three 1080p cameras w/ 120 dB of dynamic range: dual-cam 360° vision
    - One narrow cam to see far-away objects
  - Processor
    - Qualcomm Snapdragon 845
  - Storage
    - 32 GB built-in storage
    - 1TB Samsung 980 NVMe SSD
  - Connectivity
    - LTE
    - Wi-Fi
    - High-Precision GPS
  - Night-vision
    - IR LEDs for interior night-vision monitoring

Opponents

- **LiDAR – Velodyne HDL-64E LiDAR Sensor ($80000 USD)**
  - Sensor
    - Time of Flight Distance Measurement with Intensity
    - 64 channels
    - Measurement Range: Up to 120 m
    - Single or Dual Returns
    - Field of View (Vertical): +2.0° to -24.9° (26.9°)
    - Angular Resolution (Vertical): 0.4°
    - Field of View (Horizontal): 360°
    - Angular Resolution (Horizontal/Azimuth): 0.08° – 0.35°
    - Rotation Rate: 5 Hz – 20 Hz
  - Laser
    - Laser Product Classification: Class 1 Eye-safe
    - Wavelength: 903 nm
    - Dynamic Laser Power Selection for Larger Dynamic Range

Conclusion

- **SWOT**
  - Strengths
    - Long detection range
    - All-weather operation
    - Low power consumption
    - Low cost
  - Weaknesses
    - Low angular resolution
    - Hard to detect stationary object
  - Opportunities
    - Autonomous driving
    - Vital sign detection
  - Threats
    - Vision
    - LiDAR

References

- Zhou, Yi, et al. "Towards Deep Radar Perception for Autonomous Driving: Datasets, Methods, and Challenges." *Sensors* 22.11 (2022): 4208. (https://www.mdpi.com/1424-8220/22/11/4208)
- AWR2944EVM (https://www.ti.com/tool/AWR2944EVM)
- AWR2944 Spec (https://www.ti.com/product/AWR2944)
- Comma ai (https://comma.ai/shop/comma-three)
- Velodyne 64-line LiDAR (https://www.neuvition.com/media/blog/lidar-price.html)