Building a multipatient contactless vital signs sensor for at-home use with mmWave radar sensors

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Introduction

Human vital signs are usually measured through monitoring systems that historically have relied on wired connections to a patient's body to report heart and breathing rates through a combination of electrocardiogram and oxygen saturation sensors. These sensors can be difficult to keep in constant contact with newborns, severely burned patients, those who suffer from epilepsy or patients in psychiatric wards. For those patients who are mobile, monitoring vital signs can be challenging as the patient moves around their home.

A millimeter-wave (mmWave) radar sensor can detect very fine movements, even from a patient's chest. Since chest movements are affected by both breathing (fundamental frequency) and heart-rate movement (additional harmonics), the fine measurement of chest movements enables contactless measurement of vital signs.

The primary enabler of this functionality is the ability of the sensor to detect the position and speed of a patient's chest through a combination of frequency modulated continuous wave (FMCW) sensing and multiple input, multiple output (MIMO) antenna radar systems.

The sensor can also detect movements in bed and inform caregivers of potential bed sores, or even monitor multiple patients at once, such as an elderly couple. Additionally, a mmWave sensor can detect a person falling and notify caregivers in real time.

The importance of integration

One of the parameters to ensure accurate and repeatable measurements in FMCW systems is the chirp ramp linearity. Having the full analog chain integrated on a monolithic microwave integrated circuit not only decreases design-to-design variations, but also helps increase overall measurement linearity, since it is possible to perform effective monitoring and calibration over age and temperature.

Looking at the block diagram of the Texas Instruments (TI) IWR6843 in **Figure 1**, you can see that the only external component for the transmitter-receiver section is a standard 40-MHz crystal. Besides this external 40-MHz crystal, the IWR6843 offers full transmitter-receiver integration, with:

- A ramp generator.
- A fractional phase-locked loop.
- A 20-GHz voltage-controlled oscillator (VCO), which when routed externally (or selected from an external source) can synchronize multiple front ends and enable coherent sampling on much larger virtual antennas.

The IWR6843 also includes the full radio-frequency (RF) chain for the transmitter and receiver, including:

- A software-programmable power amplifier that enables multiple levels of transmit power to allow maximum flexibility when adapting the link budget to the environment and RF regulations.
- Dynamically programmable phase shifters for beamsteering.
- A low-noise amplifier, which when programmed in conjunction with power amplifiers enables link budget fine-tuning.
- Mixers thatl generate an intermediate frequency (IF) from the transmit and receive chirps.
- IF analog filters.
- Analog-to-digital converters (ADCs) with up to a 25-MHz sampling frequency.

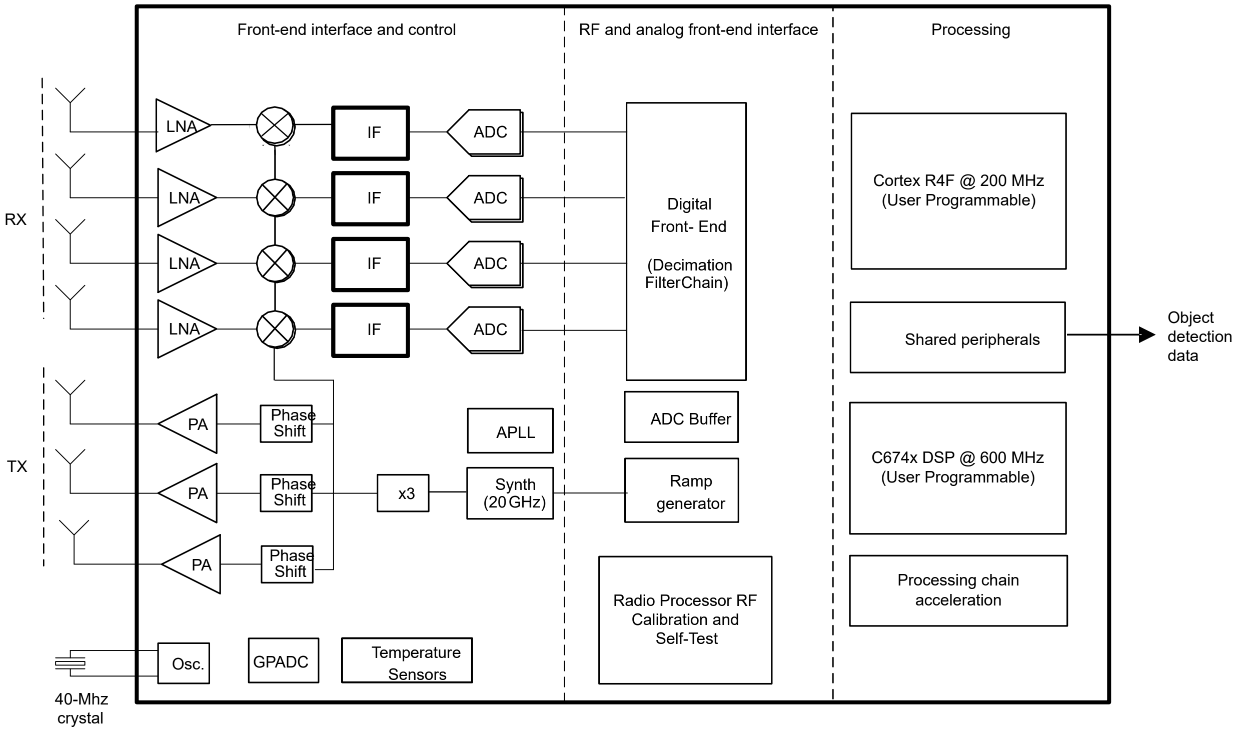

Figure 1. *IWR6843 block diagram.*

Having the full RF chain integrated on the MMIC system-on-a-chip enables a level of diagnostics capability required for functional safety.

Fully digital signal-chain processing integration on the IWR6843 offers:

- A radar hardware accelerator that supports 16-bit range, Doppler or angle-of-arrival fast Fourier transform (FFT), and a constant false alarm rate (CFAR) among classical radar signal processing.
- A 600-MHz fully programmable digital signal processor to enable fully customizable signal processing.
- A fully programmable 200-MHz Arm® Cortex®-R4F microcontroller for clustering, tracking and application-level code.

Besides the die-level integration, a variant of the IWR6843, the IWR6843AOP, comes with antennas on the package, bringing further integration and reducing the printed circuit board (PCB) area for space-constrained applications or when PCB routing of RF signals is challenging.

FMCW

FMCW provides the simplest modulation scheme to achieve wide range and high accuracy when measuring distance. FMCW also provides the mean for speed measurement in the radial dimension (the line between the radar and the target) – either a high speed, like that of a car, or a lower speed, like how a chest rises and falls while breathing. The tracking of such small movements is often referred to as Doppler or micro-Doppler detection.

Chirps

Chirps describe the modulation used in FMCW; the instantaneous frequency f(t) varies linearly with time, so this is a linear frequency chirp. The frequency difference between the transmitted chirp and the received chirp is directly proportional to the time of flight (the time to reach the target and come back), and thus the distance to the target.

Equation 1 expresses the transmitted wave amplitude as:

$$\mathrm{y_T(t) = A_T \times \sin(2\pi \times (f_0 + K \times t) \times t)} \tag{1}$$

where K is the slope by which the transmitted frequency increases by unit of time (for the IWR6843, this value can be anything between 0 and 250 MHz/µs), A_T is the amplitude at which the signal transmits (transmit power), and f_0 is the lowest frequency transmitted at the beginning of the chirp (57 GHz or 60 GHz, depending on the selected VCO).

Equation 2 expresses the received wave amplitude as:

$$y_R(t) = A_R \times sin(2 \times \pi \times (f_0 + K \times (t - \delta)) \times (t - \delta)) \tag{2}$$

where, for $\delta = \frac{2 \times d}{v}$ (which is twice the time of flight), d is the distance to the target, and v is the celerity of the light in the medium.

Mixer

A mixer multiplies the frequency difference between the transmit and receive signals (**Equation 3**):

$$y_M = y_T \times y_R \tag{3}$$

Following the basic trigonometric rules, the output of the mixer are a sum of two sines: one whose frequency is the difference between f_TX and f_RX, and the other being the sum.

Passing the output of the mixer through a low-pass filter recovers the IF signal, whose frequency is the difference between the transmitter and receiver.

Equation 4 expresses the product-to-sum formula as:

$$sin\left(x\right) \times sin\left(y\right) = \frac{1}{2} \times \left(cox\left(x - y\right) + cox\left(x + y\right)\right) \tag{4}$$

The output of the mixer passes through a low-pass filter yielding an IF, which is the difference between the transmitter and receiver (and thus a quantity directly proportional to the time of flight).

Equation 5 is the resulting IF signal:

$$y_{IF} = \cos\left(2\pi\left[-f_0\delta \; - \; 2 \times K \; \times \delta \times t \; + \; K \; \times \delta^2\right]\right) \tag{5}$$

The ADC digitizes the signal; note that the signal's frequency is much lower than the frequency of the chirps, and so is easily passable through normal ADCs. For example, the maximum sampling frequency of the ADC in the IWR6843 is 25 MHz.

From **Equation 5**, you can clearly see where the Doppler element used for measuring heart and breathing rate from chest movements is coming from.

FFT and peak detection

Once the signal only carries the relevant information (the y_{IF} frequency is the image of the time of flight), the signal will go through a range FFT and then CFAR or thresholding algorithms.

Figure 2 illustrates the time-of-flight difference between the different antennas.

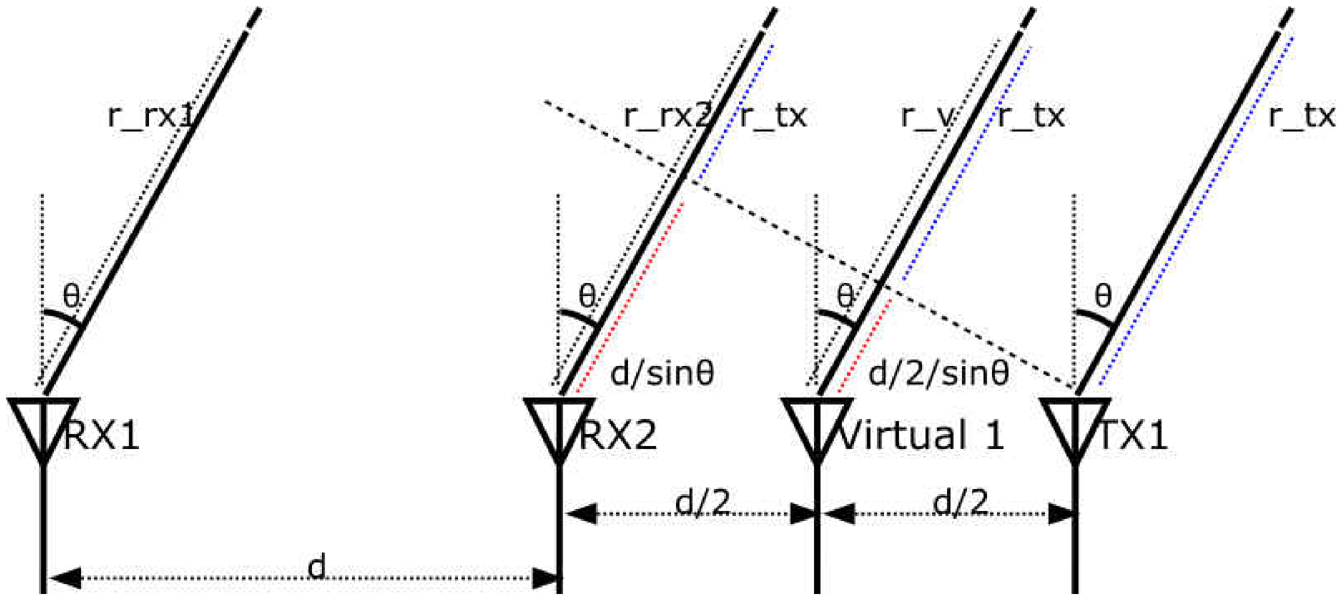

Figure 2. *MIMO Illustration of phase increases for each receive antenna.*

At a high level, the angle of arrival is derived from the difference of time of flight measured at each receive antenna.

At the mathematical level, from each antenna **Equation 6** defines a steering vector as:

$$a\left(\theta\right) = \left[e^{j \times 2\pi \times d \times \frac{sin(\theta)}{\lambda}} e^{j \times 2\pi \times d \times 2 \times \frac{sin(\theta)}{\lambda}} e^{j \times 2\pi \times d \times 3 \times \frac{sin(\theta)}{\lambda}} \ldots e^{j \times 2\pi \times d \times N \times \frac{sin(\theta)}{\lambda}}\right] \quad (6)$$

The steering vector is used to combine the signal from each target at each antenna. In **Equation 7**, which expresses the sum of all signals coming from each target through all antennas, x_i is the signal received by the i'th antenna:

$$y\left(t\right) = a^H x\left(t\right) = \sum_1^N a_i \times x_i\left(t\right) \quad (7)$$

Equation 8 calculates the average power as:

$$P\left(a\right) = \frac{1}{L} \times \sum_1^N \left|y\left(t\right)\right|^2 = a^H E\left\{x\left(t\right) \times x^H\left(t\right)\right\} a = a^H R a \quad (8)$$

Conventional receive beamforming, also known as the Bartlett beamforming method, is the oldest direction-of-arrival estimation algorithm based on narrowband arrays. This algorithm maximizes the output power of the beamformer relative to a certain direction, expressing the maximization relationship in **Equation 9** as:

$$\theta_{Barlett} = argmax_a[P(a)] \quad (9)$$

To compute P(a(theta)) for each theta, Equation 10 approximates R as:

$$R_{zz} \approx \sum_{k=0}^{n} X\left(t\right) \times X^H\left(t\right) \quad (10)$$

where X is the matrix of signals (**Equation 11**):

$$X(t) = \begin{pmatrix} x_1(t_1) & x_1(t_2) & \cdots & x_1(t_n) \\ x_1(t_1) & x_1(t_2) & \cdots & x_1(t_n) \\ \vdots & \vdots & \ddots & \vdots \\ x_M(t_1) & x_M(t_2) & \cdots & x_M(t_n) \end{pmatrix} \quad (11)$$

From these equations, you can see how a MIMO radar enables location derivation in three dimensions.

Beamsteering, in the direction that you want to sense

Capturing scene data with a radar sensor normally entails a course scan every frame period across the full field of view provided by the antenna beamwidths. This course scan captures reflections from objects both relevant and irrelevant, from which you need to extract and formulate particular objects, or in this case patients who need their vital signs measured. After identifying the location of the patient, it is possible to focus the beam using transmit beamforming, as mentioned previously.

If the patient is not at boresight, then beamsteering can be activated. This functionality is enabled by 6-bit configurable phase shifters with a step size of 5.625° on each transmitter, with 64 settings available to cover the 0- to 360-° phase shift. The phase shifters are located before the respective power amplifiers and programmed individually for each transmit channel based on where to focus the main beam, see **Figure 3**. The phase shifters are typically analog structures based on a vector modulator, which uses a digital-to-analog converter to create a phase shift on the signal before being amplified.

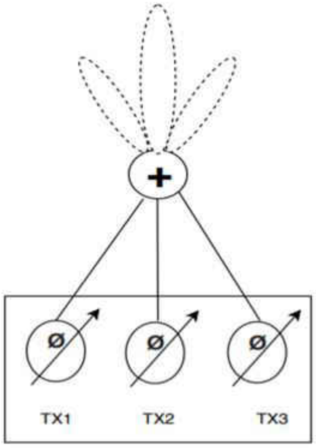

Figure 3. *Phase shifters included in the transmit stage.*

You can program the phase shifters in real time for cases where there are multiple subjects at different azimuthal angles to the radar sensor – either frame to frame (typically 100 to 200 ms), or less when using subframes. For example, the beam can sweep from –60° to +60° on a subframe basis in steps of 20°, with a full scene scan lasting less than 200 ms, as shown in **Figure 4**. This facilitates the sensing of vital signs from multiple subjects across a room from wall to wall, with the subjects located at different angles and illuminated sequentially by the transmit beams.

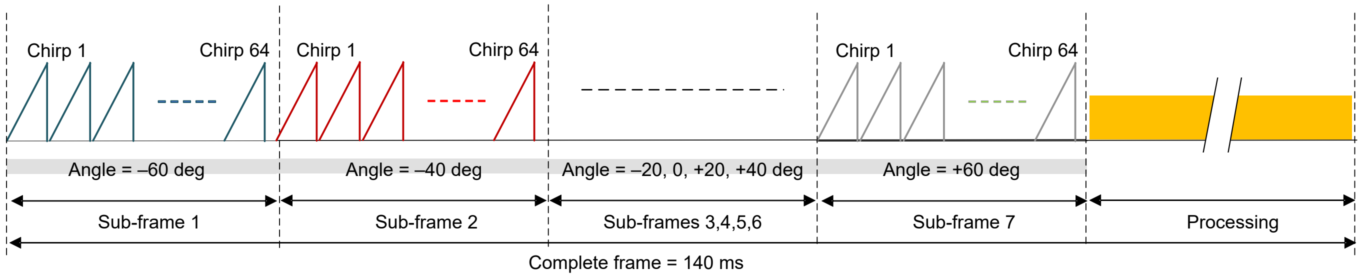

Figure 4. *Changing a beamsteered angle every subframe by 20°.*

Calibration

To maintain performance across voltage and temperature variations, TI mmWave radar devices support boot-time calibrations at the RF initialization phase (calling the RfInit() application programming interface) as well as during runtime (during application execution). **Figure 5** illustrates an example ordering of calibration types, which can include:

- Analog phase-locked loop calibration.
- Synthesizer VCO.
- Local oscillation distribution calibration.
- ADC DC offset.
- IF amplifier high- and low-pass cutoff frequencies.
- Peak detector.
- Transmit and receive gains.
- Quiescent current mismatch.

- Transmit phase shifters.

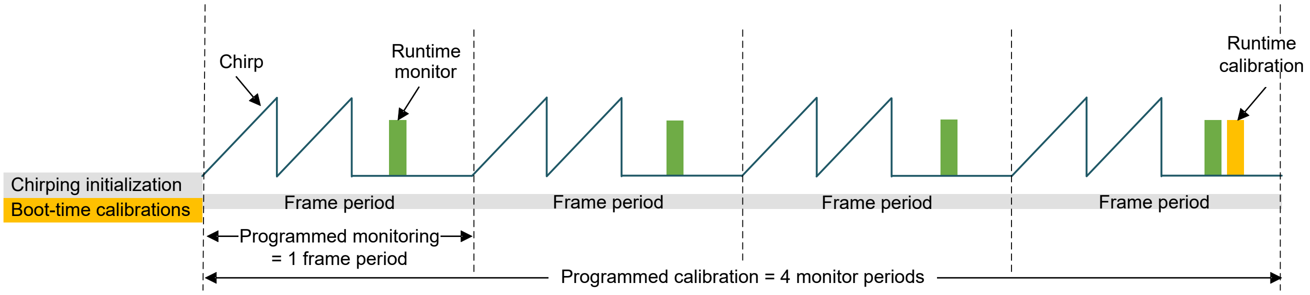

Figure 5. *Timing sequence of functional chirping, monitoring and calibration.*

Figure 6 illustrates some of the integration in the RF front end for calibration of transmit, and receive analog front-end parameters. Along with power detectors for the PA outputs and LNA inputs, in combination with loopback paths, it is possible to continually monitor and compensate the complete front end.

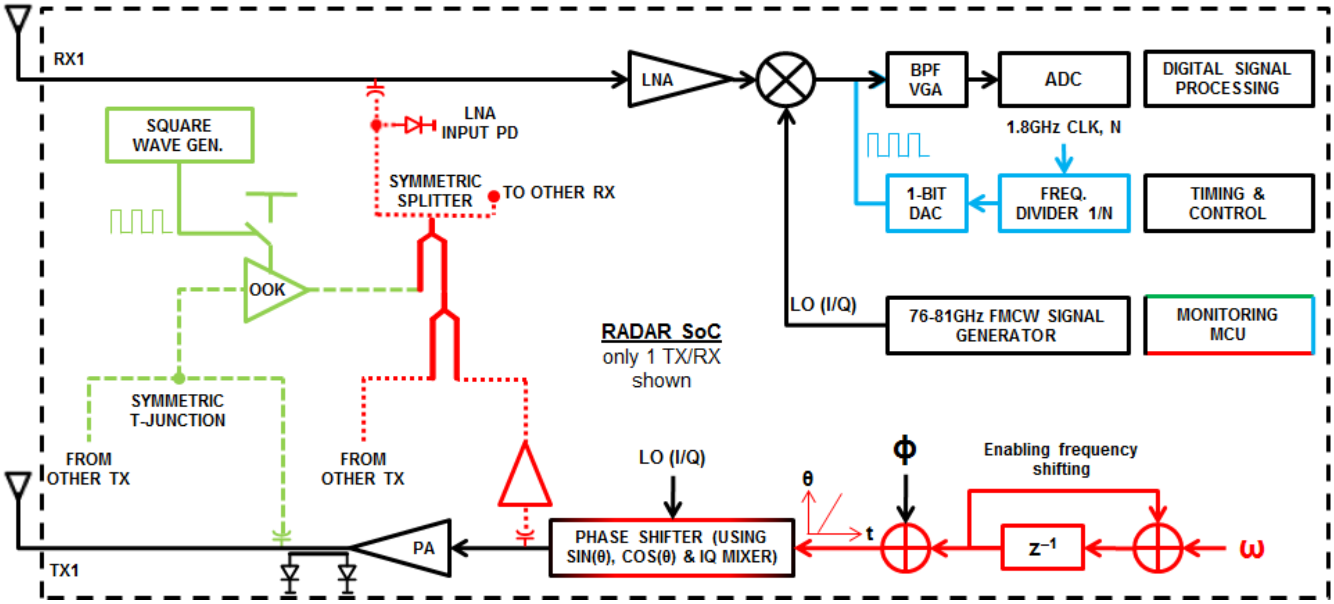

Figure 6. *Overview of the diagnostics and monitoring included in the IWR6843.*

Conclusion

TI mmWave devices include a high level of integrated features needed for FMCW radar, and require only one external 40-MHz crystal to clock the complete front end. Such products can detect fine micro-Doppler motion in three dimensions, including the detection of the breathing and heart rates of humans.

The further integration of multiple TX chains with phase shifters allows for transmit beamforming and beamsteering, enabling SNR improvements in a reduced field of view while maintaining MIMO operation for 3D sensing.

Finally, the integration of monitoring and calibration for all analog components enables consistent performance across the lifetime of the device. This level of analog integration enables a multipatient contactless vital signs sensor for at-home use.

Related Websites

- Check out the **Vital Signs Support Guide** and **Vital Signs with People Tracking User's Guide** on TI Resource Explorer.
- Learn about safety features in the training, "**Enabling Functional Safety in TI mmWave Devices**."
- Watch the "**mmWave Vital Signs Lab**" training video.
- Texas Instruments, ***Self-Calibration in TI's mmWave Radar Devices***
- Texas Instruments, ***Cascade Coherency and Phase-Shifter Calibration***

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