Coupling-Cancellation-Antenna for Improving Doppler Radar Motion Measurement Accuracy

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***Abstract*—One of the challenges in direct conversion Doppler radar lies in the dc offset resulted from antenna coupling. The dc offset may saturate the baseband amplifiers, preventing sufficient amplification of the received signal. In this work, a Coupling-Cancellation-Antenna (CCA) was implemented in the radar front end to enhance radar detection accuracy by minimizing the TX-RX antenna coupling. The idea is to have two transmitting antennas fed by signals with 180° phase difference such that the two signals cancel at the RX antenna. As a result, a larger receiver gain can be used to improve the signal to noise ratio without saturating the baseband output. Experimental validations of the CCA concept demonstrate 37-dB reduction in the TX-RX coupling. Furthermore, the CCA method reduces the detection error from 15.8% to 2.4%.**

***Index Terms*—coupling-cancellation-antenna, doppler radar, cardiac motion, homodyne duplexer cross-talk cancellation.**

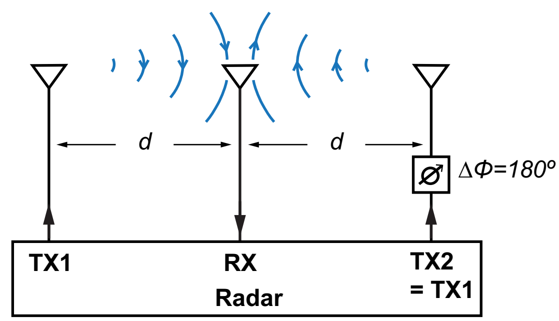


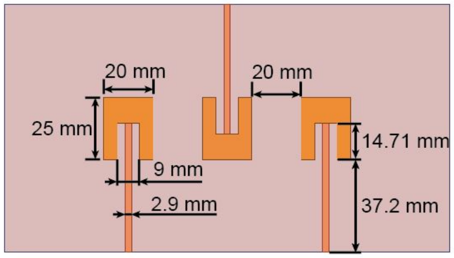
Fig. 1. DC canceling antenna scheme.

I. Introduction

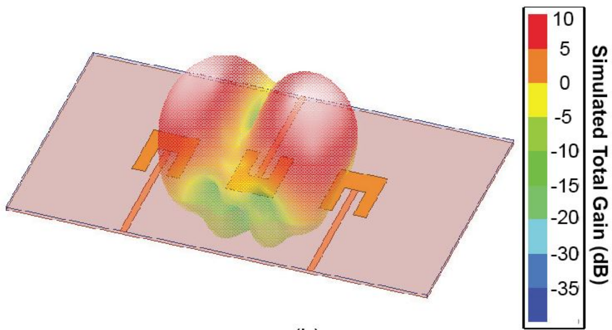
The direct conversion receiver is a popular receiver architecture for continuous-wave (CW) Doppler radars for non-contact vital sign sensing [1]. A limitation in direct conversion receiver is the dc offset caused by insufficient isolation between the transmit (TX) and receive (RX) antennas (also known as self-interference). The dc offset limits the dynamic range of the receiver by saturating baseband amplifiers. In a vital-sign monitoring radar, the dc offset reduces signal-to-noise ratio (SNR) of the received signal, thus limiting the performance of vital sign detection [2].

Several approaches have been published to tackle antenna coupling issues with cancellation techniques in radar system innovations [3]. A symmetric antenna placement technique was introduced for self-interference cancellation in [4], which was implemented on a MIMO system for full duplex communication. The approach employed an internal phase shift of 180° after the signal received by two symmetrically placed RX antennas with respect to the center placed TX antenna. By combining the two receiving signals, self-interference is nullified. The same principle applies to TX antenna cancellation as well. A realization was reported in [3] with a rat race coupler to achieve 30 dB passive suppression. The 180° phase shift can also be realized by asymmetric placement of two TX antennas where TX-RX distance of the two TX antennas is half a wavelength [5]. However, the physical design with fixed placement would not allow carrier frequency to be changed post-fabrication. In [1], the TX signal phase-adjusting method was applied using only 1 TX-RX pair configuration. In the setup, a separated path takes a portion of the TX LO signal with adding an 180° phase shift achieved cancellation of the most direct coupling in receiver chain to realize an accurate respiration measurement. Through coarse-tuning the magnitude of out-of-phase signal from TX, the dc difference was reported to be dropped by 93%. However, it was mentioned that the magnitude for the portion of TX signal mixing at RX side needs to be actively adjusted after start of the measurement.

Inspired by these prior works, this paper presents a similar TX-RX antenna cancellation scheme that dramatically improves the radar detecting accuracy. This proposed radar front-end design is named “Coupling-Cancellation-Antenna” (CCA). It mainly composes of the aforementioned symmetric



(a)



(b)

Fig. 2. (a) CCA Layout with specified dimensions (b) Overlay view of radiation pattern when TX antennas has the same amplitude yet 180° phase difference

antenna placement structure and supplementary phase and amplitude adjusting components. Rather than having 1 TX and 1 RX antenna like the conventional case, the proposed design has 2 TX antennas fed by signals with 180° phase difference. The proposed design leads to a much smaller coupling between the transmitting (TX) antenna and the receiving (RX) antenna so that larger receiver gain can be applied without saturating the baseband amplifiers. From the cascaded noise figure (NF) point of view, larger gain results in better NF or SNR. Noise is suppressed in this way so that cleaner signals can be obtained. Finally, the proposed CCA design has the advantage to break the limitation for single fixed frequency and be able to calibrate before doing accurate measurement.

II. Coupling-Cancellation Antenna

Fig. 1 shows the block diagram of the proposed CCA design consisting of two TX antennas and one RX antenna. The signal from radar transmitter is divided equally into two branches by a power splitter. One branch of the signal passes through a phase shifter which creates the desired 180° phase shift so that the signals from the two TX antennas cancel each other at the location of the RX antenna. To compensate for the loss of practical phase shifters, an variable attenuator is added to the second branch of the TX signal.

A. CCA Design

Microstrip patch antennas are used in this design to demonstrate the concept. The layout and dimensions of the antennas are presented in Fig. 2 (a). A center frequency of 2.63 GHz is used for all the designs. The antennas are designed on 62-mil FR4 substrate with a dielectric constant of 4.4.

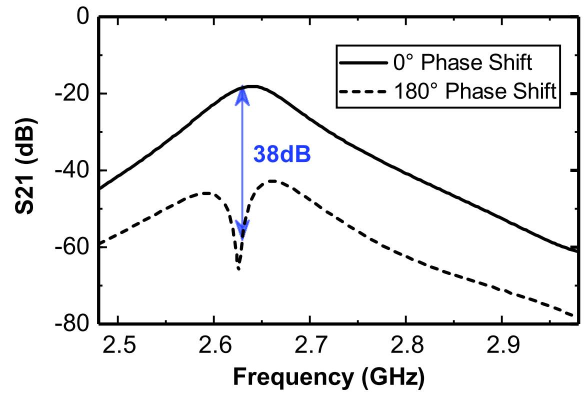


Fig. 3. S-parameters when 2 TX antenna ports are fed by signals with the same amplitude and 0° or 180° phase difference.

Fig. 3 shows that the simulated S_{21} for the design with 0° and 180° phase shift. When the two TX signals are in phase, i.e., 0° phase shift, a strong coupling of -18.4 dB is observed between the TX and RX antennas at 2.63 GHz. When the TX signals are out of phase, i.e., 180° phase shift, the coupling between the antennas decreases by 38.1 dB ($S_{21} = -56.5$ dB). This is consistent with the simulated radiation pattern shown in Fig. 2 (b). Here, a null in the radiation pattern can be observed at the location of the RX antenna when the two TX signals are out of phase. The proposed concept has been validated by the simulation results.

To experimentally validate the concept, the proposed antenna design is fabricated and measured. Fig. 4 (a) and (b) show the fabricated antenna in two different configurations. In Fig. 4 (a), only one TX antenna is connected, whereas in Fig. 4 (b), two TX antennas are connected with out-of-phase signals created by a TELEMAKUS TEP4000-5 digital phase shifter.

Fig. 4 (c) shows the measured leakage (S_{21}) between the TX and RX antennas. The 1TX-1RX case shows a leakage of -25.69 dB at 2.73 GHz. At the same frequency, the CCA configuration shows a S_{21} of -62.78 dB, representing a 37-dB decrease of TX-RX leakage. This is very close to the simulated performance (Fig. 3).

B. Practical Considerations

In many previous works where similar TX-RX leakage cancellation concepts were utilized, a discussion on the radiation characteristics of the composite antenna is generally lacking [3], [4]. In practice, it should be noted that the out-of-phase TX antennas effectively form a phased array alters the overall radiation pattern from that of the element antenna. Fig. 5 illustrates the scenario. For a separation of 0.364 λ, the strongest radiation occurs at 43° from the broadside. This is consistent with the simulated radiation pattern in Fig. 2 (b). Due to this effect, the CCA antenna no longer maintains the broadside radiation characteristics of a typical patch antenna.

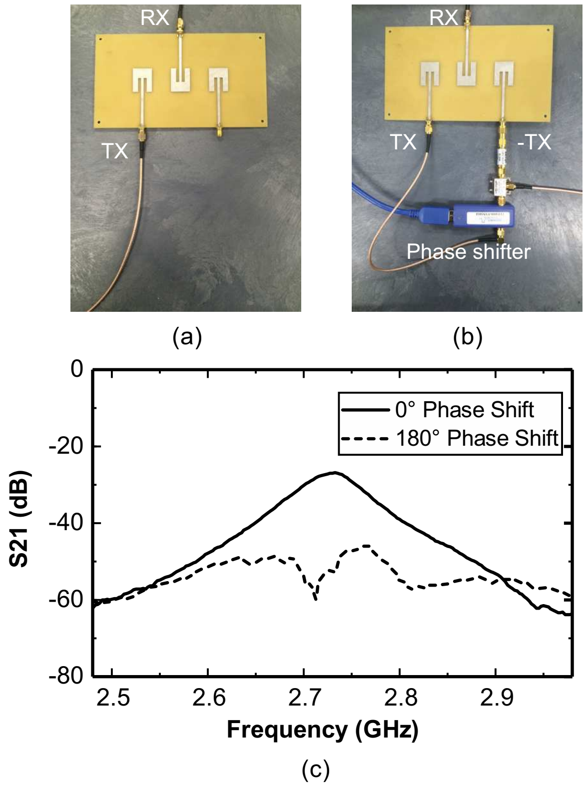


Fig. 4. (a) S_{21} Measurement Setup for 1-TX-1-RX antenna. (b) S_{21} Measurement Setup for CCA. (c) Coupled power is $-22.69\,\text{dB}$ in the base case when 1 TX antenna is applied while the proposed Coupling-Cancellation-antenna scheme achieves $-62.78\,\text{dB}$ at $2.73\,\text{GHz}$.

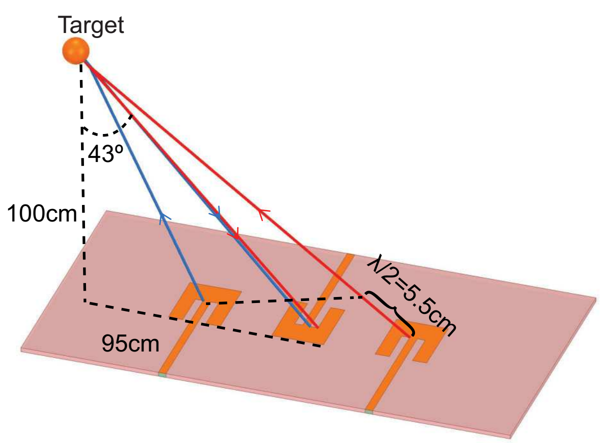


Fig. 5. An example illustration that the target needs to be offset at a angle so that the power of echo from the target is the strongest (The graph is not drawn in scale).

III. Improvement of Radar Detection Accuracy using CCA

A. Measurement setup

To demonstrate the effectiveness of the CCA in improving radar detection accuracy, four different radar measurement setups are used, as shown in Fig. 7. The target used in the

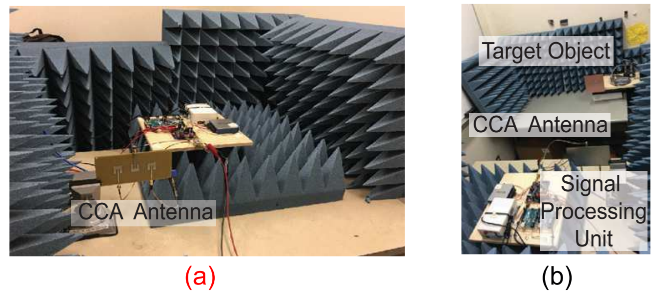


Fig. 6. (a)the Radar System with CCA setup in the experiment (b)from the opposite direction to show the target position.

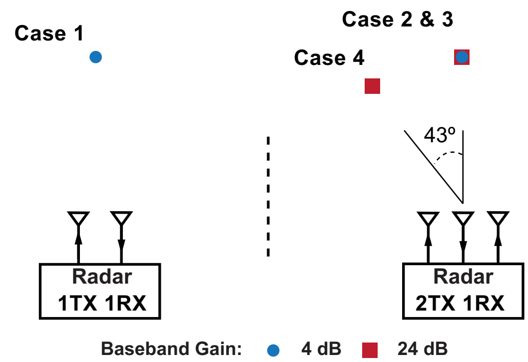


Fig. 7. Illustration of 4 cases of setup during measurement.

measurements is a $12.7 \times 12.7\,\text{cm}^2$ metal plate. The plate is actuated by a Griffin Motion linear actuator. The linear actuator is programmed to oscillate at a frequency of 1 Hz, similar to a typical adult's heart rate, with an amplitude of 4 mm. A quadrature transceiver is used as the radar frontend. The baseband output signals are recorded at 1 ksps by a National Instruments USB-6002 data acquisition device.

The following list gives a brief description of the setup of the 4 conditions which is also shown in Fig. 7:

1) Conventional setup of 1 TX antenna and 1 RX antenna, 4 dB baseband gain (base case),
2) 2 TX antennas and 1 RX antenna, 0° phase difference, target in front of antennas, 4 dB baseband gain applied,
3) 2 TX antennas and 1 RX antenna, 180° phase difference, target at destructive position, 24 dB baseband gain applied,
4) CCA setup of 2 TX antennas 1 RX antenna, 180° phase difference, target at optimal position, 24 dB baseband gain applied.

B. Measurement Results

Table I summarizes the measurement results in terms of the mean SNR and the mean error. As an example, Fig. 8 shows the measured signal after bandpass filtering in the I/Q domain. Fig. 8 (b) represents the data of CCA design obtained in Case 4. It has 24 dB baseband gain without saturating the baseband signals. Fig. 8 (a) presents the data of the base case. The maximum baseband gain it can tolerate before saturation is

TABLE I
MEASUREMENT RESULTS OF THE FOUR CASES

No.	Case Description	Mean SNR	Mean Error
1	1TX 1RX (base case)	15.6 dB	15.84%
2	2TX 1RX. 0° phase difference. Target in front of antennas	16.8 dB	13.38%
3	CCA. Target at null position.	16.3 dB	11.87%
4	CCA. Target at optimal position	23.6 dB	2.41%

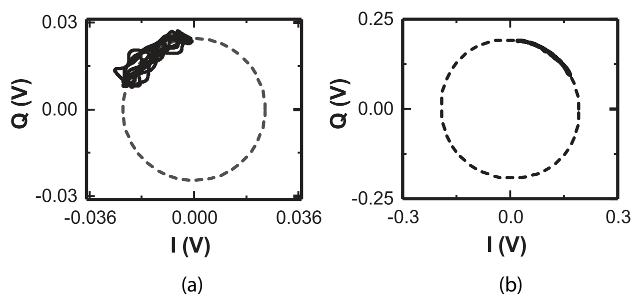


Fig. 8. Comparison of sampled data between (a) 1 TX 1RX structure with 4 dB baseband gain (base case), and (b) 2TX 1RX structure with 180° phase difference between 2TX, having 24 dB baseband gain, target at optimal position

4 dB. Obviously, CCA results in a much cleaner output signal with better SNR.

CCA measured in case 4 gives a mean SNR of 23.6 dB and mean detection error of 2.41%, both of which are much better than the base case of 15.6 dB mean SNR and 15.84% detection error. Other two cases perform similarly as the base case, which are not plotted here for space consideration. In all, the experiment results validate that CCA can achieve dramatic improvement for the radar performance.

IV. CONCLUSION

The Coupling-Cancellation-Antenna (CCA) was implemented to further enhance accuracy by minimizing the antenna coupling. The idea is to have 2 transmitting antennas fed by signals with 180° phase difference such that coupling between TX and RX antennas is minimized. As a result, the larger receiver gain can be utilized to improve SNR without saturating the baseband output. The experiment results validate that CCA can achieve dramatic improvement for the radar performance with placing target at its optimum direction.

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