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Advantages of Utilizing Higher-order Response for a Harmonic Radar

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***Abstract*— In nonlinear radars, fundamental tone(s) are sent out to the environment. Clutters that are generally linear in behavior reflect these tone(s) towards the radar. However, the target has a tag containing antenna(s) and a nonlinear device such as a diode, a transistor, or a mixer. This nonlinear device then generates a series of nonlinear responses such as harmonic and intermodulation tones based on the incident fundamental signal. The radar's receiver is designed to accept these nonlinear responses and reject fundamental tone(s) for target identification and clutter rejection purposes. Traditionally, harmonic radars exploited 2nd-order harmonic response for clutter rejection and target identification. Since the 2nd-order harmonic and fundamental tones are relatively close to each other, these radars rely on high-quality filters to attenuate the 2nd-order harmonic from getting radiated from the transmitter and prevent fundamental responses from leaking into the receiver, which avoids any false detection. Hence expensive diplexers and cascaded reflectionless filters were used to achieve necessary attenuation of undesired clutter responses. This cascaded structure leads to complex and bulky radar systems. To solve this issue, the authors are proposing to exploit higher-order harmonics to achieve desired performance without using expensive, bulky diplexers and filters, thus making the system portable and easy to operate. In this paper a 2nd-order based and a 3rd-order based harmonic radar are compared and their performance is evaluated to decide the tradeoff of utilizing higher-order harmonics compared to the traditional 2nd-order harmonic response.**

Keywords—2nd-order harmonic response, 3rd-order harmonic response, clutter rejection, nonlinear radar, target identification.

I. INTRODUCTION

In the last decade, nonlinear radars have attracted great interests given their new applications ranging from tracking insects to monitoring human vital signs [1, 2]. A popular type of nonlinear radar is harmonic radar, which refers to a radar design in which the radar signal is transmitted around a fundamental tone f_0, and the reception chain will be operated on one of the harmonics Mf_0, where M is a positive integer. Harmonic radars have three important requirements in their design: (1) high receiver sensitivity to the desired harmonic tone due to the weak response of harmonics; (2) high linearity to suppress undesired harmonic tones in the transmitter and fundamental tone in the receiver [3]; and (3) high linearity to reject the leakage of the fundamental tone and undesired harmonic tones for the LO path of the receiver down-converter.

The literature has presented case studies such as the selection of filters [4] and the roles of filters for a harmonic radar [5]. In most of the studies, 2nd-order harmonic radar was the most used in the designs and implementation. However, given the relative

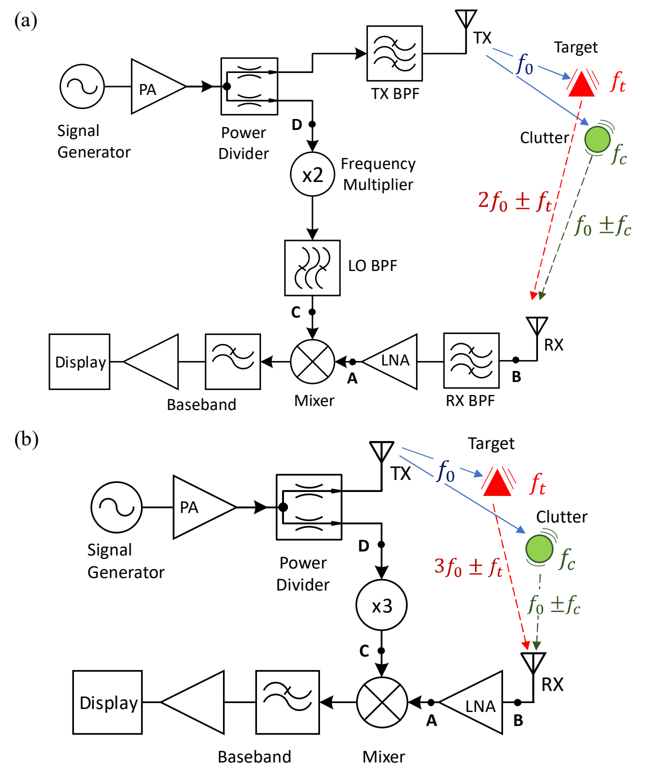

Fig. 1. Block diagram of (a) 2nd-order harmonic radar; and (b) 3rd-order harmonic radar.

closeness between the fundamental tone and its 2nd harmonic, complex filtering blocks are required to maintain its linearity [3]. Therefore, the 3rd-order harmonic radar was hypothesized as an alternative [6] to avoid the concern of the closeness between the fundamental tone and its harmonics.

This paper presents a quantitative study of the advantages of using higher-order harmonic radars, for which it investigates three cases: the first case is a 2nd-order continuous-wave (CW) harmonic radar; the second case is the same architecture without using the filters on the TX, RX and LO paths; and the third case is a filter-less 3rd-order CW harmonic radar. System-level simulations and link budget analysis were performed to compare the three cases and observe how much the filter stages affect the 2nd-order harmonic radars, in contrast to the 3rd-order filter-less radar. In the studies, a nonlinear target and a linear clutter in the scenario of indoor human sensing are considered. But the analysis can be extended to other nonlinear radar applications without loss of generality.

II. Harmonic Radar Systems

In order to compare the behavior of 2nd and higher-order harmonic radar systems, both systems were simulated in the AWR Design Environment using Visual System Simulator (VSS). The simulations were performed using the real parameters of the components according to their datasheets, specifically for nonlinear components, such as the power amplifier (PA), frequency multiplier, and mixer. Fig.1 (a) and (b) show the diagram block for the 2nd and 3rd-order harmonic radars, respectively. Both systems transmit a fundamental tone and receives combined signals from a nonlinear target and a linear clutter.

A. 2nd-order harmonic radar system

In Fig.1 (a), the 2nd-order harmonic radar is based on the detection of a target's second-order harmonic response. This second-order system is divided in three RF signal paths, i.e., the transmitter (TX) path, the local oscillator (LO) path, and the receiver (RX) path, with center frequencies of 8 GHz, 16 GHz, and 16 GHz, respectively. The TX path consists of a PA and a TX band-pass filter (BPF). The PA (Mini-circuits ZX60-05113LN+) has a gain of 24.1 dB, an output P1dBm of 12 dBm, an OIP3 of 24.6 dBm, and a Noise Figure of 1.8 dB. After the power divider (Mini-circuits EP2K1+), the RF signal goes to the TX BPF, which blocks the harmonics generated by the PA. The TX BPF (Mini-circuits VLF-8400+) operates in the frequency range of 0.1 MHz to 8 GHz. The LO path has a ×2 frequency multiplier (HMC814LC3B) with a conversion gain of 6 dB, and an LO BPF (HFCN-1322+) with a bandwidth from 14.3 GHz to 18.5 GHz. On the RX path, there are an RX BPF and an LNA. The RX BPF (HFCN-1322+) is the same component as that used for the LO BPF, and the LNA (HMC490LP5E) has 25 dB of gain, 26 dBm of output P1dBm, and 34 dBm of OIP3. The RF and LO inputs of the mixer (EV1HMC554ALC3B) generate the IF signal, which goes to the baseband stage.

B. 3rd-order harmonic radar system

Fig.1 (b) presents the block diagram for the 3rd-order harmonic radar. Similar to the 2nd-order harmonic radar, this is divided in three RF signal paths. However, this 3rd-order system detects a target's third-order harmonic response. The center frequencies of the TX, LO, and RX paths are 8 GHz, 24 GHz, and 24 GHz, respectively. The architecture for the 3rd-order harmonic radar is similar to the 2nd-order harmonic radar, with the main difference that it omits the filter stages (i.e., TX filter, LO filter, and RX filter). The LO path has a ×3 frequency multiplier (Marki-Microwave NLTL-6275) with a conversion loss of -20 dB. The RX path has an LNA (EV1HMC863ALC4) with 24 dB of gain, 25.5 dBm of output P1dBm, 35.5 dBm of OIP3, and 4.5 dB of Noise Figure. After that, RF and LO signal are mixed to generate the IF signal (EVAL01-HMC1063LP3).

C. Target and clutter

The RF signal propagation was modeled with the following parameters taken into account: the radar transmits a signal power of 8.2 dBm, the transmitting and receiving antennas have a gain of 5 dB, and the distance from the nonlinear target and the linear clutter to the radar is 1 m. The path loss from the radar to the nonlinear target is 40.50 dB, from the nonlinear target to the radar of 2nd-order harmonic radar is 46.52 dB, and from the nonlinear target to the 3rd-order harmonic radar is 50.04 dB. The radar received signal power is -78.85 dBm, and -82.2 dBm in the cases of the 2nd-order and 3rd-order radars, respectively. In addition, the radar receiving antenna's attenuation for the linear clutter is 3.2 dB in case of the 2nd-order system and 10 dB for the 3rd-order system. Assuming a radar cross-section (RCS) is 1 m^2 (i.e., a person) for the clutter, resulting in the received clutter signal power of -43.3 dBm. The nonlinear target and the linear clutter have periodic movements of 2 Hz and 3 Hz, respectively. These parameters were chosen for indoor vital signs detection in the presence of multiple persons, with one person wearing a nonlinear tag and another person being the clutter.

TABLE I. Key parameters for each case of the harmonic radars

Parameters	Harmonics radars		
	2nd-order with filters	*2nd-order without filter*	*3rd-order without filter*
Filter bandwidth			
TX BPF (GHz)	0.0001 – 8.4	No Filters	No Filters
LO BPF (GHz)	14.3 - 18.5		
RX BPF (GHz)	14.3 - 18.5		
RX path: out-of-band rejection			
Fundamental	-19.47 dB	25.0 dB	0 dB
2nd-order harmonic	24.99 dB	25.0 dB	-77.15 dB
3rd-order harmonic	-87.84 dB	-58.43 dB	24.0 dB
LO path: rejection of undesired tones and conversion gain			
Conversion gain	6 dB	6 dB	-20 dB
Fundamental	-61.74 dB	-15.18 dB	-39.76 dB
2nd-order harmonic	31.72 dB	31.72 dB	-11.88 dB
3rd-order harmonic	-17.73 dB	11.68 dB	4.99 dB

Table I. compares the key parameters for each case of harmonic radar presented. The first section describes the bandwidth of the filters used in each path (i.e., TX, LO, and RX), which is only for the 2nd-order harmonic radar. The second section presents the out-of-band rejection to the RX path between the points A and B in Fig. 1. The last section shows the conversion gain of the frequency multipliers and the rejection of undesired tones in the LO path among points C and D in Fig. 1.

III. Result Analysis and Comparison

Fig. 2 shows the baseband response of the detected signal for the three cases of harmonic radars presented in this paper, where the target's frequency of motion f_t and the clutter's frequency of motion f_c are 2 Hz and 3 Hz, respectively. Furthermore, the clutter returns signal at a center frequency of f_0, and the target's center frequency of the 2nd-order and 3rd-order system are $2f_0$ and $3f_0$, respectively, as can be seen in Fig. 1.

In the first case of the 2nd-order system with filters, the voltage levels are clearly distinguished among the responses of the nonlinear target (18.00 mV) and the clutter (1.63 μV), as shown in Fig. 2(a). This is because the received signal passes

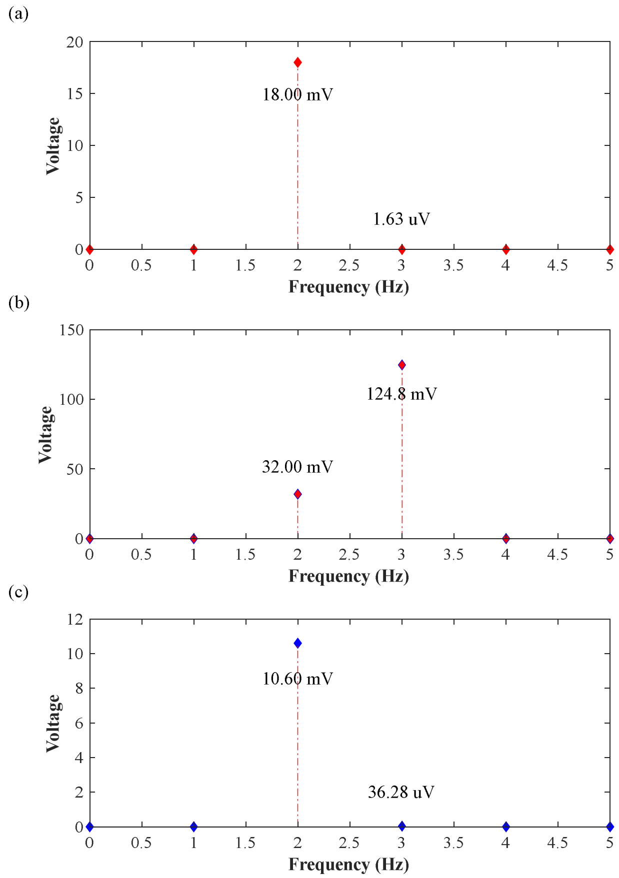

Fig. 2. Baseband response of the harmonic radar systems for (a) 2nd-order system with filters; (b) 2nd-order system without filter; and (c) 3rd-order system without filter.

through points A and B in the receiver path of Fig. 1 (a), which offers an out-of-band rejection of 44.46 dB for the fundamental tone with respect to the 2nd harmonic, according to calculation based on parameters in Table I. In contrast, Fig. 2 (b) illustrates the second case of the 2nd-order system without any filter, where the clutter's voltage level (124.80 mV) is much stronger than the target's voltage level (32.00 mV). This is mainly due to the absence of rejection along the RX path for the fundamental tone, which is the clutter's center frequency. Also, for the LO path, the amplitude of rejection band for the fundamental decreased, as can see in Table I. Finally, in the case of the 3rd-order system without filter, the target's and clutter's voltage levels are 10.60 mV and 36.28 µV, respectively, as shown in Fig. 2 (c). Since the fundamental tone experiences an out-of-band rejection in the RX path of 24 dB, and a 44.75 dB rejection in the LO path, with respect to the desired 3rd-order harmonic.

Table II. describes the tradeoff to consider for comparison of the three harmonic architectures, which are: (1) clutter rejection calculated as the ratio in dB between the baseband components corresponding to the target and clutter; (2) power consumption by all active components of the system except for the signal generator (the main difference in power consumption is due to the amplifiers in the systems). The comparison shows that the 3rd-order system has the advantage of not requiring filters, but at the tradeoff of higher power consumption.

TABLE II. COMPARISON OF THE THREE HARMONIC RADARS

	Clutter rejection (dB)	Power consumption§ (W)
2nd-order with filters	80.86	1.6
2nd-order without filter	-11.82	1.6
3rd-order without filter	49.31	2.1

§ The power consumption does not include the RF signal generator.

IV. CONCLUSION

This work presents three architectures of harmonic radars, which are simulated on system level using AWR with VSS, to demonstrate the tradeoffs in using higher-order harmonic radar. It is observed that the role of high-quality filters is essential for 2nd-order systems. On the other hand, in a higher-order harmonic radar such as the 3rd-order system considered in this paper, the target signal can be detected without the need for high-performance filtering stages. However, the path loss increases for higher-order systems and the cost of building blocks such as the frequency multiplier could be higher. For example, for the frequency considered in this paper, a ×3 frequency multiplier is more difficult to find and expensive compared with a ×2 frequency multiplier. With these results, future works include the design of a filter-less 3rd-order FMCW harmonic radar, and electronic characterization to compare the performance with its 2nd-order counterpart that relies heavily on high-quality filters.

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