Nonlinear Detection and Classification of Transmitter Signals

Aleksandra Doric[1], Nataša Maleš-Ilic[2], Aleksandar Atanaskovic[2] and Predrag Eferica[2]
[1]Innovation Centre of Advanced Technologies Ltd
Niš-Crveni krst, Serbia, Bulevar Nikole Tesle 61/5
18000 Niš, Serbia
{alexdjoric@yahoo.com}

[2]Faculty of Electronic Engineering, University of Niš
Aleksandra Medvedeva 14, 18000 Niš, Serbia
{aleksandar.atanaskovic, natasa.males.ilic, efa@elfak.ni.ac.rs}

ABSTRACT: *In this paper, with the help of the nonlinear target detection and classification, we have developed a new automotive radar concept. The nonlinear products of the transmitter signals and harmonic and intermodulation of the third-order are detected by the harmonic radar are carried by the target carriers of the nonlinear tag. The reflection works to detect the cares of the second harmonics of the radar transmitter signals - two LFM modulated carriers, whereas the vulnerable targets, such as pedestrians, children and similar, are detected by reflection of the third-order intermodulation products. The nonlinear transfer character works to generate the intermodulation products by the power amplifier in the radar transmitter. The second harmonic of the transmitted signals exploit the linearization techniques.*

Keywords: Automotive Harmonic Radar, Vulnerable Targets, Nonlinear Passive Tag, LFM Signal

Received: 26 March 2021, Revised 3 July 2021, Accepted 9 July 2021

DOI: 10.6025/jio/2021/11/3/78-84

1. Introduction

The modern automotive industry has a great need for development of the automotive applications such as pedestrian safety systems, collision warning, turning-off and lane changing assistance. The automotive radar system requires the simultaneous and precise targets localization with high accuracy and resolution and also their classification to distinguish between the different object classes such as the automobiles and vulnerable road users (VRU) for their better protection.

The design of the harmonic car radar includes the passive reflector (tag) mounted on the back of the vehicles preceding that returns the second harmonic of the frequency transmitted from the vehicle behind [1]. This concept aims to avoid rear/end collisions and it is immune to the clutter reflection from the different objects and obstacles, and also it protects from blinding by the cars that travel in the opposite direction.

Significant effort has been devoted to the development of the harmonic radars for various applications. The second harmonic radar that emits signal at one frequency and passive tags reflecting signal at the emitted signal second harmonics, have been used for insect and animal searching [2], remote sensing and detection of vital signs in medical application [3], as well as target detection in ultrawideband UWB systems [4]. The harmonic radars that transmit signals at two or more carrier frequencies have been applied for classification and localization of the VRUs [5], detection of RF electronic component and devices [6] and in RFID system for detection and accurate localization by using the harmonic tags [7].

The VRUs localization system consists of a harmonic car radar that transmits two distinct frequency carriers (f_1 and f_2) modulated by the LFM baseband signal. The targets are carrying the nonlinear tag that generates the nonlinear intermodulation products of the transmitted signals that may be transmitted back to the radar. The radar system processes the reflections and separates the conventional targets from the VRUs.

However, when the power amplifier in the radar transmitter amplifies two or more modulated carriers, due to its nonlinear characteristic it generates the intermodulation products at the amplifier output that cause spectral regrowth with the useful fundamental signals. The various linearization techniques for minimizing the third- and fifth-order distortions of the power amplifiers have been reported in the literature [8]: feedback, feed-forward, predistortion, etc.

In the previous work, authors of this paper have deployed the linearization technique that uses the second- and fourthorder nonlinear signals (IM2, IM4) of the fundamental signals [9-12] and validated its effects on the several single stage RF and Doherty PA configurations throughout the simulation process and experiments. Very good results are achieved in the reduction of the third- and fifth-order intermodulation products of the amplifiers for multitone signals as well as for digitally modulated QAM, WCDMA and OFDM signals.

In this paper, the reduction of the third-order intermodulation products in the harmonic radar transmitter is accomplished by application of the linearization method that uses the second harmonics (IM2 signals) of the fundamental LFM modulated carriers.

In Section 2 the new harmonic radar concept is described and the theoretical background of the applied linearization approach is explained. The Section 3 relates to the results of the IM3 and IM5 products suppression obtained by the proposed linearization approach. Then, in the Section 4, some conclusions are reported.

2. Harmonic Radar Concept

Figure 1 shows the new harmonic radar concept that includes the transmitter at the car front end that emits two LFM modu-

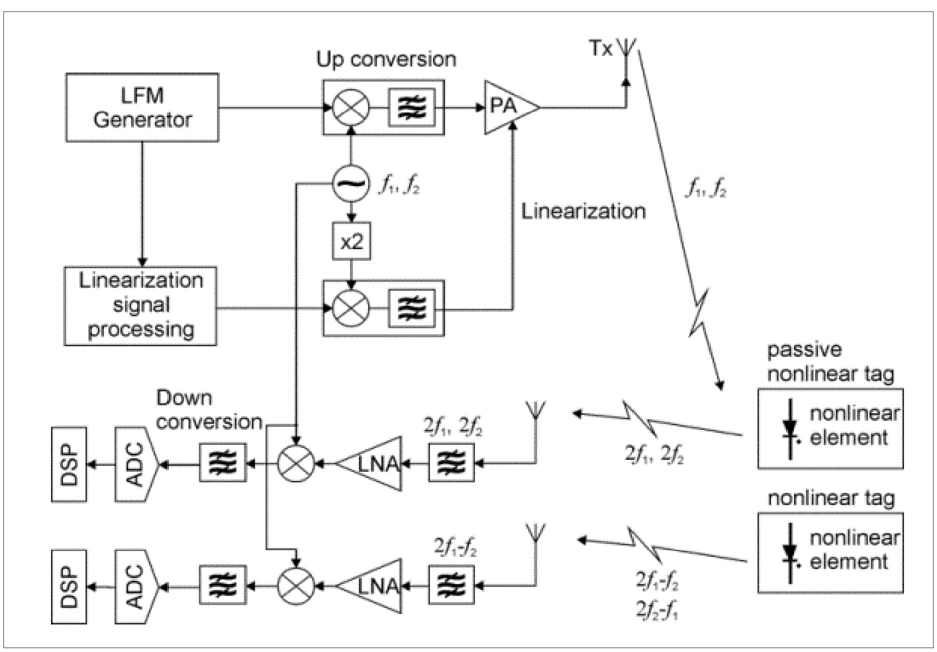

Figure 1. Harmonic radar concept for target classification and range and velocity determination

lated carriers at frequencies f_1 and f_2. A linear frequency modulated (LFM) waveform is the simplest form of frequency modulation, commonly used in the automotive industry, where the frequency is repeatedly swept linearly in frequency range, f_{sw}, (each frequency sweep is commonly known as a chirp, T_{chirp}). The transmitted signals travel to the harmonic tags (transponders, sensors, reflectors) that consist of the nonlinear element, receiving and transmitting antennas. The nonlinear element generates the nonlinear signals such as harmonics and intermodulation products of the transmitted signals. The adequate design of the transmitting antenna on the nonlinear tag provides reflection of the second harmonic or intermodulation products of the receiving signals. The vulnerable targets may carry the intermodulation nonlinear tag whereas the second harmonic tag may be installed on the back side of the car.

The power amplifier in the radar transmitter is a nonlinear device and produces the nonlinear products - harmonics and intermodulation products at frequencies $2f_1 - f_2$ and $2f_2 - f_1$ that are close to the fundamental emitted frequencies f_1 and f_2. The signal for vulnerable target detection and identification appears at the intermodulation frequencies and can interfere with the intermodulation products generated at the transmitter due to the nonlinear transfer characteristic of the power amplifier. Accordingly, in this paper, the transmitter intermodulation products are suppressed by the linearization technique that utilizes the second harmonics of the transmitted LFM modulated fundamental carrier [9-12]. The adequate baseband signals for the linearization are up converted at the frequencies of the second harmonics of the fundamental signal carriers, adjusted in amplitude and phase and inserted at the input and output of the PA transistor. The frequencies of the local oscillators, necessary for the down conversion at the second harmonic receiver, $2f_1$ and $2f_2$, are generated at the transmitter for the linearization purposes.

Two identical LFM signals are upconverted to the second harmonics of the two fundamental carriers and sent to the two types of targets. One target type is normal (does not carry nonlinear tags) while the other type carries the harmonic tags. The nonlinear element in the tag produces the harmonic and intermodulation signals, whereas the reflecting tag antenna determines the frequency of the reflected signal: at the carriers' second harmonics or at the intermodulation products of the third-order. The reflected signals from the targets are detected at the radar receivers that select the certain channel by the appropriate bandpass filter. The target range and velocity may be determined according to the equations from the procedure of measuring beat frequencies and applying FFT according to the algorithm depicted in literature, [4], [13].

The operating principle of the proposed linearization approach could be described by a Taylor-series polynomial model, [14], in case when the memory effects are neglected. The linear frequency modulated signal can be represented in the form:

$$V_{LFM}(t) = A\cos\left(\omega_o t + \frac{f_{sw}}{2T_{chirp}} t^2\right) = A\cos(\phi(t)) \tag{1}$$

Complex version of the signals is:

$$I + jQ = A(\cos(\phi(t)) + j\sin(\phi(t))) \tag{2}$$

where $I = A_I\cos(\phi(t))$ and $Q = A_Q\sin(\phi(t))$ are the in-phase and quadrature-phase components of the baseband signal.

The complex envelope of the LFM triangular signal characterized with the $T_{chirp} = 1\mu s$ is created in ADS to modulate the fundamental carriers at the frequencies f_1 and f_2. The baseband signal required for the linearization is formed as squared of the complex envelope of the fundamental LFM signal:

$$v_{lin\_IM2} = (I + jQ)^2 = \left[(I^2 - Q^2) + j2IQ\right] \tag{3}$$

The baseband signal for the linearization modulates the second harmonics of the fundamental carriers at $2f_1$ and $2f_2$. After modulating, the signals are combined and adjusted on the appropriate amplitude and phase in the analogue RF domain throughout the two linearization branches. The signals for the linearization set on the appropriate values are inserted at the input and output of the power amplifier transistor over the bandpass filters centered at $f_c = \frac{f_1 + f_2}{2}$.

The signals injected at the amplifier transistor gate - the fundamental useful signals and the signals for linearization adjusted in amplitude and phase (a_{g2h}, θ_{g2h}) are given by:

$$v_{gs}(t) = \sum_{i=1}^{2}\{v_{si}[I\cos(\omega_i t) - Q\sin(\omega_i t)] + a_{g2h}e^{-j\theta_{g2h}}[(I^2 - Q^2)\cos(2\omega_i t) - 2IQ\sin(2\omega_i t)]\} \quad (4)$$

The signal at the drain of the transistor consists of the fundamental signal gained linearly (the first term in eq. (5)), and the signals for linearization tuned in amplitude and phase (a_{d2h}, θ_{d2h}) and injected at the amplifier transistor drain.

$$v_{ds}(t) = \sum_{i=1}^{2}\{v_{oi}[I\cos(\omega_i t) - Q\sin(\omega_i t)] + - a_{d2h}e^{-j\theta_{d2h}}[(I^2 - Q^2)\cos(2\omega_i t) - 2IQ\sin(2\omega_i t)]\} \quad (5)$$

where ($v_{oi}[I\cos(\omega_i t) - Q\sin(\omega_i t)]$,, i = 1, 2 is the output signal at the fundamental frequencies.

The drain current at the frequencies of the third-order intermodulation products $2\omega_1 - \omega_2$ and the fifth-order $3\omega_1 - 2\omega_2$, are represented by the equations (6) and (7), respectively. We supposed $v_{s1} = v_{s2} = v_s$ and $v_{o1} = v_{o2} = v_o$ to simplify the equations. Another the IM3 and IM5 products, at frequencies $2\omega_2 - \omega_1$ and $3\omega_2 - 2\omega_1$, have the same form.

$$i_{ds}(t)\big|_{(2\omega_1-\omega_2)} = \left(\frac{3}{4}v_s^3 g_{m3} + a_{g2h}e^{-j\theta_{g2h}}v_s g_{m2} + -\frac{1}{2}a_{d2h}e^{-j\theta_{d2h}}v_s g_{m1d1} + \frac{1}{2}a_{g2h}e^{-j\theta_{g2h}}v_o g_{m1d1} + \frac{3}{2}v_s v_o^2 g_{m1d2} + \frac{3}{2}v_s^2 v_o g_{m2d1}\right)(I^2 + Q^2)(I\cos((2\omega_1 - \omega_2)t) - Q\sin((2\omega_1 - \omega_2)t)) \quad (6)$$

$$i_{ds}(t)\big|_{(3\omega_1-2\omega_2)} = \left(\frac{5}{8}v_s^5 g_{m5} + \frac{3}{2}a_{g2h}^2 e^{-j2\theta_{g2h}}v_s g_{m3} + +\frac{1}{2}a_{d2h}^2 e^{-j2\theta_{d2h}}v_s g_{m1d2} - a_{g2h}a_{d2h}e^{-j(\theta_{g2h}+\theta_{d2h})}v_o g_{m1d2} + +\frac{1}{2}a_{g2h}^2 e^{-j2\theta_{g2h}}v_o g_{m2d1} - a_{g2h}a_{d2h}e^{-j(\theta_{g2h}+\theta_{d2h})}v_s g_{m2d1}\right)(I^2 + Q^2)^2(I\cos((3\omega_1 - 2\omega_2)t) - Q\sin((3\omega_1 - 2\omega_2)t)) \quad (7)$$

According to the analysis carried out in the previous research [9-12], the third-order distortion of the fundamental signal is dominantly caused by the cubic transconductance (g_{m3}) term in the polynomial transistor model and can be reduced by selecting the adequate amplitude and phase of the second harmonic modulated by the appropriately modified baseband signal for the linearization, which are injected at the input and output of the amplifier transistor.

3. Linearization Results

In the automotive industry different frequency bands have been used for applications whereas the 24 GHz and 77 GHz bands are dominant [13]. In this paper, we have analyzed the proposed harmonic radar concept operating at much lower frequency than standardized. The main reason for that is the intention to test the linearization effects of the technique that exploits the carrier second harmonics in case of the LFM continuous wave signal, which is utilized standardly in automotive radars for range and velocity determination. For the application and testing purposes of the proposed linearization technique [9-12], we have exploited previously designed power amplifier that operates in the frequency range 0.7 to 1.1 GHz [12]. The amplifier was designed in Agilent Advanced Design System-ADS based on the nonlinear MET model of the Freescale transistor MRF281S LDMOSFET. The maximum achieved gain is around 22 dB at 1 GHz, whereas the maximum power added efficiency (PAE) for the maximum output power of around 36 dBm is 50% at 1 GHz.

Two identical LFM signals characterized by the frequency bandwidth f_{sw} = 50MHz are upconverted by RF carriers f_1 = 095GHz and f_2 = 1.05GHz for sending to the targets that may be normal (does not carry nonlinear tags), and targets that carry harmonic tags. The nonlinear elements produce the harmonic and the intermodulation signals. The tag antenna operating frequency band enables that the reflected signals are at the carriers' second harmonics $2f_1$ = 1.9GHz and $2f_2$ = 2.1GHz or at the intermodulation products of the third order $2f_1 - f_2$ = 0.85 GHz and $2f_1 - f_2$ = 1.15GHz.

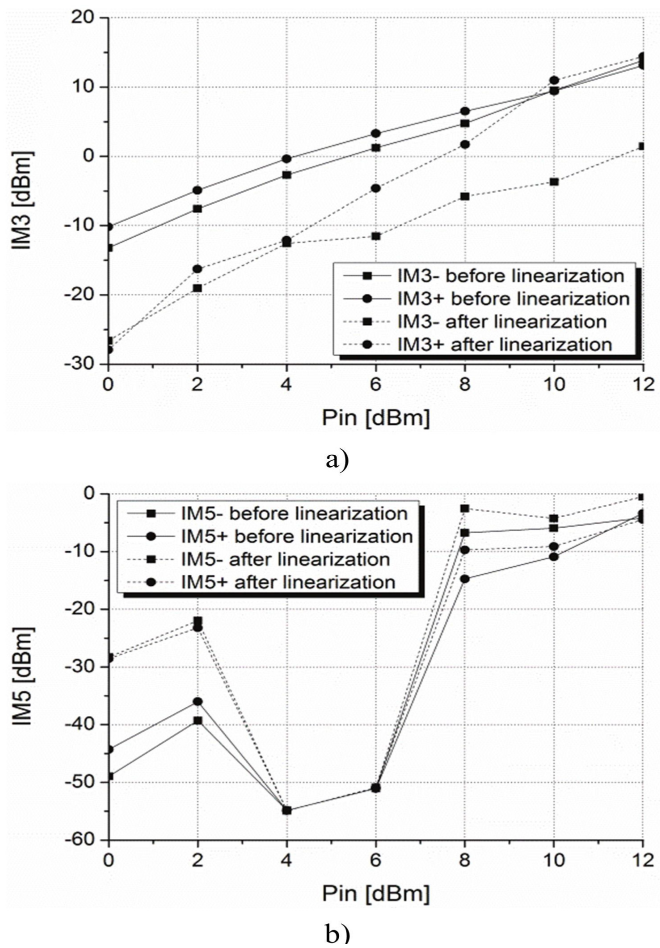

Figure 2. The intermodulation products of the power amplifier at the transmitter of the automotive radar for the LFM signal in terms of input power levels before and after the linearization: a) third-order; b) fifth-order

The analysis has been carried out for different fundamental signal power levels at the amplifier input from 0 dBm to 12 dBm. The simulation results represented in Figure 2a show that the IM3 products are lessened more than 15 dB in the case of 0 dBm input power, whereas for the rise of the input power level the suppression rate is falling down to 10 dB up to approximately 6 dBm input power. In case of the higher power levels the linearization cannot be attained. It should point out that 6 dBm input power enables the output power of 26 dBm per carrier, which is around 3 dB below 1-dB compression point of the amplifier, [12]. Moreover, including the fact that the RF carriers are shifted by 100 MHz (25% of theamplifier bandwidth) the achieved linearization results are considered to be satisfied.

The simulated results of the performed linearization approach effect on the fifth-order intermodulation products, IM5, presented in Figure 2b, indicate that the IM5 products are slightly worsen in reference to the state before the linearization for almost all considered input power levels. The significant impairment is observed at lower power level from 0 dBm to 3 dBm. It should stress that the linearization has been performed, i.e. the optimization of the amplitude and phase of the signals for linearization has been carried out with the aim to suppress the third-order intermodulation products and to restrain the fifth-order intermodulation products at the levels below the reduced IM3 products, which is accomplished in entire power range.

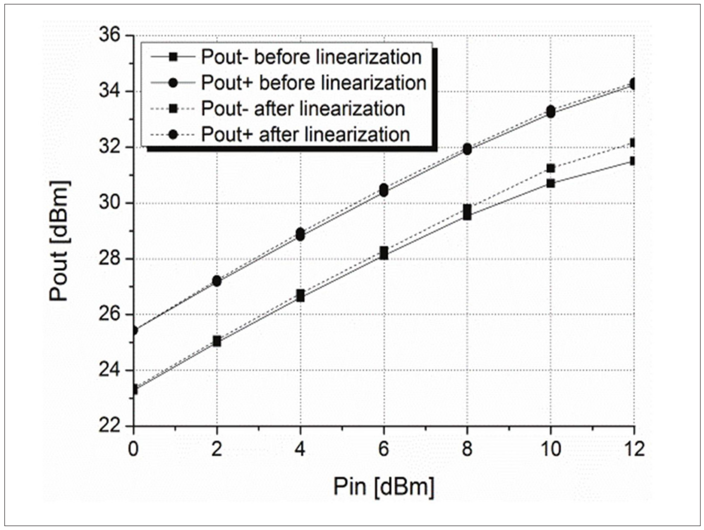

Figure 3. Output power of the power amplifier in automotive radar transmitter for two RF carriers modulated by LFM signal

Additionally, the output power of the RF carriers is also enhanced when the proposed linearization approach is applied, which is illustrates in Figure 3.

4. Conclusion

A new automotive radar concept for target detection and classification based on the idea of the harmonic radar is presented in this paper. The system generates the nonlinear products of the transmitted signals, such as the second harmonics and intermodulation products of the third-order, because the targets are carrying the nonlinear tag. The cars may be identified by reflection of the second harmonics of the two radar transmitter carriers modulated by the LFM baseband signal, whereas the vulnerable targets, such as pedestrians, children and similar will be identify by reflection of the third-order intermodulation products. The power amplifier in the radar transmitter amplifies the two carriers and, due to its nonlinear transfer characteristic, generates the intermodulation products that may interfere with the reflected products from the VRU targets.

Accordingly, it is necessary to suppress the amplifier third order intermodulation products and to retain the fifth-order distortions to the appropriate power level below the thirdorder. The reduction of the intermodulation products has been obtained by using the linearization technique that exploits the second harmonics of the fundamental signal carriers. The satisfactory reduction of the IM3 products is achieved and IM5 products are kept at the power level below the suppressed IM3 products even though two transmitter carriers are shifted in frequency 100 MHz (25% of the amplifier bandwidth). Also, the output power of the fundamental signals is increased for a certain percent of decibels.

Acknowledgement

This work was supported by the Ministry of Education, Science and Technological Development of Republic of Serbia, the project number TR-32052.

References

[1] Shefer, J., Klensch, R. J., Kaplan, G., Johnson, H. C. (1974). Clutter- Free Radar for Cars, Wireless World, 117-122, May.

[2] Tsai, Z., Jau, P., Kuo, P. N., Kao, J., Lin, K., Chang, F., Yang, E., Wang, H. (2013). A High-Range-Accuracy and High-Sensitivity Harmonic Radar using Pulse Pseudorandom Code for Bee Searching, *IEEE Trans., Microwave Theory Tech*., 61 (1) 666–675.

[3] Chioukh, L., Boutayeb, H., Deslandes, D., Wu, K. Noise and Sensitivity of Harmonic Radar Architecture for Remote Sensing and Detection of Vital Signs, *IEEE Trans., Microwave Theory Tech*, 62 (9) 1847-1855 (September).

[4] Gallagher, K., Harmonic Radar. (2015). Theory and Applications to Nonlinear Target Detection, Tracking, Imaging and Classification, Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy, The Pennsylvania State University, December.

[5] Saebboe, J., Viikari, V., Varpula, T., Seppä, H., Cheng, S., Al-Nuaimi, M., Hallbjörner, P., Rydberg, A. (2009). Harmonic Automotive Radar for VRU Classification, Radar Conference Surveillance for a Safer World, Conference Proceedings, October.

[6] Mazzaro, G., Martone, A., Mcnamara, D. (2014). Detection of RF Electronics by Multitone Harmonic Radar, *IEEE Trans., Aerospace and Electronic Syst*., 50 (1), January.

[7] Dardari, D. (2015). Detection and Accurate Localization of Harmonic Chipless Tags, *EURASIP Journal on Advances in Signal Processing*.

[8] Cripps, S. (1999). *RF Power Amplifiers for Wireless Communications*, Chapters 4-5, 115–251, Artech House.

[9] Males-Ili, N., Milovanovi, B., Budimir. (2007). Effective Linearization Technique for Amplifiers Operating Close to Saturation, *International Journal of RF and Microwave Computer-Aided Engineering*, 17 (2) 169-78.

[10] Atanaskovi, A., Maleš-Ili, N., Milovanovi, B. (2012). Linearization of Power Amplifiers by Second Harmonics and Fourth-order Nonlinear Signals, *Microwave and Optical Technology Letters*, 55 (2) 425-430 (February).

[11] Maleš-Ili, N., Atanaskovi, A., Blau, K., Hein, M. (2015). Linearization of Asymmetrical Doherty Amplifier by the Even-Order Nonlinear Signals, *International Journal of Electronics*, Taylor & Francis, 103 (8) 1318-1331.

[12] Ori, A., Maleš-Ili, N., Atanaskovi, A. (2017). RF PA Linearization by Signals Modified in Baseband Digital Domen, Facta Universitatis, Series: Electronics and Energetics, 30 (2) 209-221.

[13] Hasch, J., Topak, E., Schnabel, R., Zwick, T., Weigel, R., Waldschmidt, C. (2012). Millimeter-Wave Technology for Automotive Radar Sensors in the 77 GHz Frequency Band, *IEEE Trans., Microwave Theory Tech*., 60 (3) 845-860 (March).

[14] Pedro, J. C., Perez, J. (1994). Accurate Simulation of GaAs MESFET's Intermodulation Distortion Using a New Drain-source Current Model, *IEEE Trans., Microwave Theory Tech*., 42, 25–33 (January).