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RESEARCH ARTICLE

Vehicular Communications Over OFDM Radar Sensing in the 77 GHz mmWave Band

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ABSTRACT Radar detection and vehicle-to-everything (V2X) communication are two advanced driver-assistance system (ADAS) functions used to improve the safety of the road users and their driving experience. However, the proliferation of radars on vehicles and the functionalities expected for V2X cause several issues like interference and insufficient communication flow. To address these challenges and optimize the use of the electromagnetic spectrum, the mutualization of communication and radar detection functions in the same component using millimeter-wave (mmWave) is proposed. As orthogonal frequency-division multiplexing (OFDM) waveform seems to be the most suitable waveform to enable this cooperation, we propose to investigate the performance of OFDM radar compared to that of current frequency-modulated continuous wave (FMCW) radar. We simulate and analyse the signal-to-noise ratio (SNR) and the probability of detection (PD) of OFDM radar based on the parameters of a current mid-range automotive FMCW corner radar. We observe that FMCW radar has better SNR and PD than OFDM radar under these conditions. However, by applying a coherent integration scheme on receive, the results obtained show that good performance of OFDM radar can be achieved. To check the effect of the parameters used on the communication performance, we provide graphs of the Bit Error Rate (BER). These graphs show that the BER do not suffer from these parameters but rather that they can be beneficial to the communication.

INDEX TERMS Automotive radar, FMCW, joint radar communication, OFDM, V2X communication.

I. INTRODUCTION

A cooperation between radar and communication systems is an efficient way to increase road safety and provide intelligent traffic routing [1]. Indeed, the vehicular environment requires accurate obstacle detection to ensure the safety of users. Automotive radar currently operate with millimeter wave (mmWave) technology in the 76-77 GHz band for long range radar and in the 77-81 GHz band for short range radar [2], which gives them a high range resolution. However, automotive radar is facing interference due to the fact that devices share the same frequency band and use quite similar Frequency-Modulated Continuous-Wave (FMCW) waveforms [3]. This issue can be solved easily by shifting to Orthogonal Frequency-Division Multiplexing (OFDM) radar waveform, used currently in wideband digital communication. This has the potential to be tuned to offer a minimal cross-correlation from one emitter to the other. Another problem with automotive radar is multipath propagation that leads to some detrimental effects like ghost target generation. Also, as it is expected that more and more vehicle-to-everything (V2X) data will be exchanged in the future, for instance to share raw perception data, the current cellular vehicle-to-everything (C-V2X) framework will quickly prove insufficient in terms of available bandwidth. Millimeter wave could be the solution to address these challenges [4], as it could provide V2X communication with up to 4 GHz of frequency bandwidth in the 77-81 GHz band. The mutualization of both detection and communication functions into a same component appears to bring many advantages in addition to simplifying the automotive communication architecture and provide a relatively low cost device.

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The radar-communications system or RadCom system, which is a part of integrated sensing and communication (ISAC), was first proposed by M. Uchida, Y. Kagawa, and A. Okuno [5] and has been the subject of many studies for years (see for example [1], [5], [6], [7], [8], [9], [10], [11]) but did not lead to the development of any prototypes so far. A joint radar communication system based on FMCW radar was proposed by P. Barrenechea, F. Elferink, and J. Janssen [6] and C.-H. Wang and O. Altintas [7]. However, the modulation techniques used to encode communication data cannot reach high transfer rates, unlike OFDM waveform. To tackle this issue, [12] proposed a frequency hopping-aided FMCW RadCom system. Although it improves the communication throughput compared to other methods using this same waveform, it remains insufficient compared to the future needs of V2X and far from the throughput that OFDM would bring, in addition to complexifying the RadCom architecture and degrading the radar performances. Authors in [13] proposed to realize the joint communication and sensing by using OFDM for communication and FMCW for sensing. However, this will not bring the advantages of OFDM mentioned above to the radar, and the proposed time division will not allow the radar to continuously detect. A recent waveform called Orthogonal Time-Frequency Space (OTFS), presented as the future of modulation [14], has been proposed to achieve joint radar communication and can perform similarly of even better than OFDM waveform under certain conditions [15]. Nevertheless, one of the particularities of OFDM is that it is currently widely used in the field of communications and could thus generate a low component cost, unlike OTFS. In [11], the author shows that OFDM seems to be the most efficient and suitable waveform for a RadCom system. Several papers [1], [8], [9], [16] have shown that the use of OFDM waveform for radar applications is possible and could work very well. However, these works did not take into account current automotive radar performance requirements, especially in terms of range resolution, velocity resolution and probability of detection (PD), among other things. Authors in [17], proposed a system design for a 24 GHz RadCom that perform well in an automotive environment. They proposed a novel code-division OFDM signal and corresponding signal processing method to cancel interference between radar and communication, allowing both systems to operate simultaneously. The simulations performed show good results in terms of BER and radar ranging and velocity estimation RMSE. However, the 24 GHz carrier frequency and its consequent parameters is being abandoned in favor of 76 GHz where better performance, particularly in terms of range and velocity resolutions, can be achieved. In [8], authors proposed an approach to avoid radar interference with an OFDM signal operating at 77 GHz without taking into account the communication aspect.

In this article, a comparison between FMCW and OFDM radar based on the parameters used by current mid-range corner automotive radar is carried out. For that purpose, we evaluated the SNR and the detection probability of the two systems using similar waveform parametrization. To improve OFDM radar performances, we propose to apply a coherent integration scheme. Then, based on the parameters of the OFDM waveform obtained in both cases, an evaluation of the communication performances in terms of Bit Error Rate (BER) is done taking into account the effects of noise and Doppler shift.

The paper is organized as follows. In Section II, the theory of FMCW and OFDM radar is detailed. The OFDM radar signal processing is described and its detection performances compared to those of current automotive radar. Then, a coherent integration of scheme of OFDM symbols based on [18] is performed in order to improve the SNR and the probability of detection. In Section III, we parameterize our systems and show simulation results for both methods in Section IV. Finally, we investigate the communication aspects in terms of the BER in Section V.

II. THEORY OF FMCW AND OFDM RADAR

A. FMCW RADAR

FMCW radar is used in automotive applications since it is always active, is robust against range eclipse, and has an architecture less complex and less costly than pulsed radar. The FMCW waveform is a type of continuous waveform where the wave operating frequency is modulated over time. That frequency modulation is useful for automotive radar since it allows to determine the target range. Target velocity is estimated from the Doppler shift of the transmitted wave. The functional architecture of a FMCW automotive radar is depicted in Fig. 1. For a FMCW waveform made of M linear chirps of duration T, the transmitted signal can be written as

$$x(t) = \sum_{m=1}^{M} A(t) rect\left(\frac{t-mT}{T}\right) \times cos\left(2\pi\left[f_c + \frac{kt}{2}\right]t + \varphi_0\right), \quad (1)$$

where f_c is the carrier frequency, $rect(\frac{t-mT}{T})$ represents the m^{th} rectangular window, $A(t)$ is the magnitude of the waveform, $k = \frac{B}{T}$ denotes the linear chirp rate, and φ_0 represents the phase of the signal at the initial time.

The return signal from a single target located at a range R, with a relative velocity v_r can be written after in-phase/ quadrature (I/Q) demodulation as

$$y(t) = \sum_{m=1}^{M} \alpha A(t-mT) rect\left(\frac{t-mT}{T}\right) \times cos\left(2\pi\left[\frac{2kR}{c} - \frac{2v_r f_c}{c}\right]t + \frac{4\pi f_c R}{c}\right) + n(t), \quad (2)$$

with c the speed of light, α the attenuation of the signal (propagation, radar cross section, etc) and $n(t)$ the receiver noise. This received signal (2) is a sine wave with a frequency

$$f_b = \frac{2kR}{c} - \frac{2v_r}{c} f_c, \tag{3}$$

which is the beat frequency between the transmitted signal and the time-delayed received echo signal. As it can be seen in (3), the relative velocity and the target range are both coupled into the beat frequency. In order to decouple them, a modulation pattern called "fast-chirp" [19] is used. That consists in generating steep chirps, meaning that $kR \gg v_r f_c$ in (3), which makes the relative velocity part of the beat frequency negligible with the respect to the range contribution. Target velocity is estimated by measuring the cumulative phase shift resulting from the Doppler effect over several successive ramps. Range and Doppler estimation is done by rearranging received data as a two-dimensional (2D) datacube along fast time (intra-chirp time) and slow time (chirp to chirp sampling) and a performing 2D fast Fourier transform (FFT).

B. OFDM RADAR

OFDM is a frequency multiplexing technique where a parallel stream of multiple orthogonal subcarriers separated by a constant frequency shift Δf can be modulated with a digital modulation such as phase-shift keying (PSK) or quadrature-amplitude modulation (QAM) [1]. The OFDM signal can be expressed as

$$x(t) = \sum_{\mu=0}^{N_{sym}-1} \sum_{n=0}^{N_c-1} A(\mu N_c + n) exp\left(j2\pi f_n t\right) \times rect\left(\frac{t-\mu T_{OFDM}}{T_{OFDM}}\right), \tag{4}$$

with N_{sym} representing the number of OFDM symbols, N_c representing the number of subcarriers and $A(\mu N_c + n)$ being the complex modulation symbol. f_n is the frequency of the n^{th} subcarrier and is defined by

$$f_n = n\Delta f. \tag{5}$$

T_{OFDM} represents the total OFDM symbol duration and can be expressed by

$$T_{OFDM} = T_{CP} + T_{sym} + T_{dc}, \tag{6}$$

where T_{CP} is the cyclic prefix duration, T_{sym} is the elementary symbol duration and T_{dc} is a delay inserted between symbols leading to a duty cycle defined by

$$dc = \frac{T_{OFDM} - T_{dc}}{T_{OFDM}}. \tag{7}$$

To ensure orthogonality between subcarriers, the symbol duration and carrier spacing must satisfy

$$\Delta f T_{sym} = 1. \tag{8}$$

As mentioned in [1], the reflected OFDM signal from a target located at a range R with a Doppler shift f_D can be described as

$$y(t) = \sum_{\mu=0}^{N_{sym}-1} \sum_{n=0}^{N_c-1} A(\mu N_c + n) \times exp\left(j2\pi f_n\left(t - \frac{2R}{c}\right)\right) exp(j2\pi f_D t) \times rect\left(\frac{t - \mu T_{OFDM} - \frac{2R}{c}}{T_{OFDM}}\right). \tag{9}$$

Therefore, similarly to [1], the received complex modulated symbol can be described as

$$A_r(\mu N_c + n) = A(\mu N_c + n) exp\left(-j2\pi f_n \frac{2R}{c}\right) exp(j2\pi f_D t). \tag{10}$$

An OFDM radar processing method has been proposed in [1] and [20]. The principle is to divide the received symbols $A_r(\mu N_c + n)$ by the emitted symbols $A(\mu N_c + n)$ to recover the impulse response of the propagation channel carrying the target range and Doppler information. This method shows better performances in terms of peak-to-sidelobe ratio than the traditional matched filtering [21]. The frequency domain channel function transfer is so

$$I_{div}(\mu N_c + n) = \frac{A_r(\mu N_c + n)}{A(\mu N_c + n)} = exp\left(-j2\pi n\Delta f \frac{2R}{c}\right) \times exp\left(j2\pi \mu T_{OFDM} \frac{2v_r}{c} f_c\right), \tag{11}$$

knowing that $f_D = \frac{2v_r}{c} f_c$ with v_r the relative velocity of the target. Thus, two analytical expressions can be extracted from (11)

$$\begin{cases} k_R(n) = exp\left(-j2\pi n\Delta f \frac{2R}{c}\right) \\ k_D(\mu) = exp\left(j2\pi \mu T_{OFDM} \frac{2v_r}{c} f_c\right) \end{cases} \tag{12}$$

It is convenient to apply the inverse discrete Fourier transform (IDFT) to the first equation of (12) to evaluate the target range,

$$r(k) = IDFT\left(exp\left(-j2\pi n\Delta f \frac{2R}{c}\right)\right) = \frac{1}{N_c} \sum_{n=0}^{N_c-1} exp\left(-j2\pi n\Delta f \frac{2R}{c}\right) exp\left(j2\pi \frac{n}{N_c} p\right) \quad p = 0, \ldots, N-1, \tag{13}$$

and the discrete Fourier transform (DFT) to the second one to evaluate v_r,

$$v_r(l) = DFT\left(exp\left(j2\pi \mu T_{OFDM} \frac{2v_r}{c} f_c\right)\right) = \sum_{\mu=0}^{N_{sym}-1} exp\left(j2\pi \mu T_{OFDM} \frac{2v_r}{c} f_c\right) exp\left(-j2\pi \frac{\mu}{N_{sym}} l\right) \quad l = 0, \ldots, N_{sym}-1. \tag{14}$$

The OFDM signal processing chain is depicted in Fig. 2.

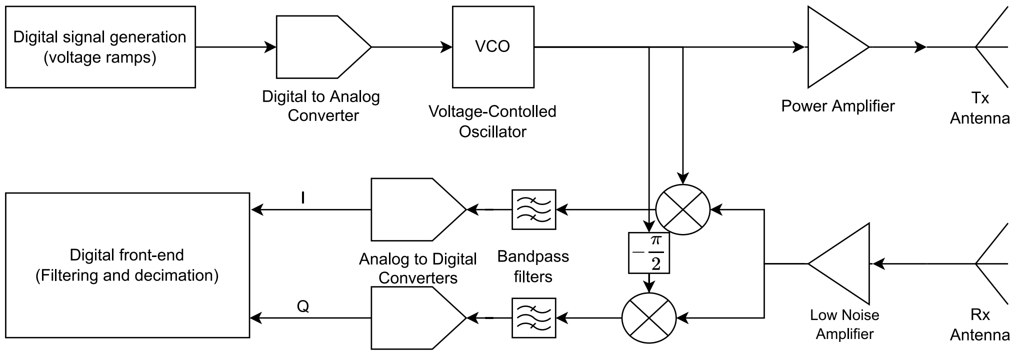

FIGURE 1. FMCW radar architecture.

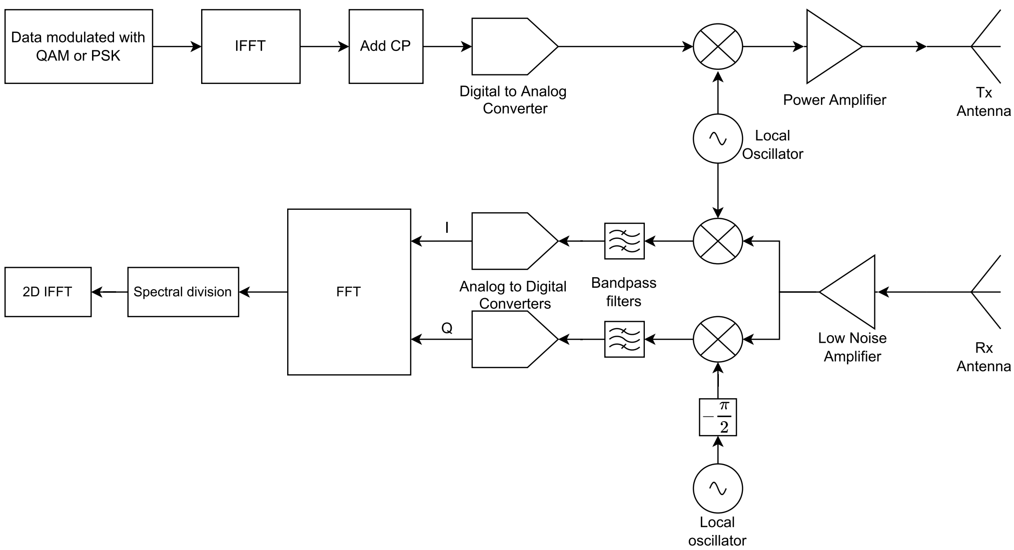

FIGURE 2. OFDM radar architecture.

III. SYSTEM PARAMETRIZATION

In this section, we define the important parameters for radar. These parameters are then set for OFDM radar in order to achieve similar performances as current FMCW radars.

A. FMCW RADAR PARAMETRIZATION

In this paper we will consider the use of the 76-77 GHz frequency band, which is the one used by current mid-range automotive radars, with a bandwidth that can go up to 1 GHz. The maximum unambiguous range is expressed for FMCW radar by

$$R_u = \frac{c}{2B} T_R f_s, \tag{15}$$

with T_R the cycle duration, B the bandwidth and f_s the sampling rate. Another key radar parameter is the range resolution, which depends on the bandwidth and given by

$$\Delta R = \frac{c}{2B}. \tag{16}$$

The maximum distance that we impose to our radar is defined by

$$R_{max} = \frac{c\tau_{max}}{2}, \tag{17}$$

where τ_{max} is the sampling delay. Indeed, to avoid demodulating the return signal with the wrong chirp, it is important not to start sampling at the beginning of a ramp but after a given time τ_{max}.

We can also define the maximum unambiguous velocity as

$$V_u = \frac{c}{2 f_c T_R}, \tag{18}$$

and the velocity resolution as

$$\Delta V = \frac{c}{2 f_c M T_R}. \tag{19}$$

B. OFDM RADAR PARAMETRIZATION

To make a comparison between the waveforms, the parameters defined for FMCW radar will be also defined for OFDM.

The first one is the maximum unambiguous range. It is expressed for OFDM radar as

$$R_u = \frac{c}{2\Delta f}. \tag{20}$$

The second one is the range resolution. As for FMCW, it depends on the bandwidth B and is given by

$$\Delta R = \frac{c}{2B} = \frac{c}{2N_c\Delta f}. \tag{21}$$

Analogously to FMCW radar, we will wait for a certain delay before starting sampling. This time for OFDM is represented by the cyclic prefix T_{CP} which also prevents inter symbol interference. This gives a relation between T_{CP} and the relative maximum range

$$T_{CP} = \frac{2R_{max}}{c}. \tag{22}$$

The maximum unambiguous velocity can also be defined for OFDM radar as

$$V_u = \frac{c}{2f_c T_{OFDM}}, \tag{23}$$

and the velocity resolution as

$$\Delta V = \frac{c}{2f_c N_{sym} T_{OFDM}}. \tag{24}$$

To ensure the orthogonality of the subcarriers on the receive side, the subcarrier spacing Δf has to be much larger than the maximum expected Doppler shift f_{Dmax}. It is commonly accepted to choose $\Delta f > 10 f_{Dmax}$ [1] knowing that

$$f_{Dmax} = \frac{2V_{max}}{\lambda}, \tag{25}$$

with V_{max} the expected maximum relative velocity and $\lambda = \frac{c}{f}$ the wavelength.

IV. SIMULATION RESULTS

In this section, the OFDM radar parameters are set to get the same resolutions as current FMCW mid-range corner automotive radar in order to compare both systems. The probability of detection and the signal-to-noise ratio are then plotted with respect to target range.

A. SIMULATION PARAMETERS

As mentioned in Section III-A both radar systems will operate at $f_c = 76$ GHz. We consider a maximum velocity equal to the maximum unambiguous velocity $V_u = V_{max} = \pm 80$ m s^{-1}. That implies for OFDM $f_{Dmax} = 40.56$ kHz, as shown in (25), and the lower limit of the subcarrier spacing $\Delta f_{min} = 405.6$ kHz. This also implies $T_{OFDM} = T = 12.5$ μs according to (18) and (23). The value of the maximum unambiguous distance is the same than the maximum expected range $R_{max} = R_u = 100$ m. This yields for OFDM $\Delta f = 1499$ kHz according to (20) and $T_{CP} = \tau_{max} = 0.67$ μs according to (17) and (22). Since the elementary OFDM symbol duration $T_{sym} = 0.67$ μs based on (8), the pause between the symbols to reach the expected OFDM total duration will be set at $T_{dc} = 11.16$ μs leading to a duty cycle of $dc = 0.1067$. This value degrades considerably the energy efficiency of the OFDM radar as discussed in the following section and is not desirable for an automotive radar. We take $dc = 1$ for FMCW radar. The current automotive corner radar range resolution requires $\Delta R = 0.3$ m which leads to $N_c = 334$ according to (21) for OFDM. This corresponds to a signal bandwidth of 500.67 MHz like for FMCW waveform. Finally, a velocity resolution $\Delta V = 0.15$ m s^{-1} is suitable for the automotive radar applications. That leads to selecting a number of symbols for OFDM, corresponding to the number of ramps for FMCW, $N_{sym} = M = 1052$ according to (24) and (19). The numerical values of the simulation parameters in Table 1. An antenna with a gain of 10 dB is set at the end of the transmission chain and another antenna with the same gain is placed in front of the receiving chain.

TABLE 1. FMCW and OFDM radar parametrization.

Symbol	Parameter	Value
f_c	Carrier frequency	76 GHz
N_c	Number of range samples Number of OFDM subcarriers	334
Δf	Subcarrier spacing	1499 kHz
T_{sym}	Elementary OFDM symbol duration	0.67 µs
τ_{max}	FMCW sampling delay	0.67 µs
T_{CP}	OFDM cyclic prefix duration	0.67 µs
dc	Duty cycle	1 for FMCW radar 0.1067 for OFDM radar
T_R	FMCW cycle duration	12.5 µs
T_{OFDM}	OFDM cycle duration	12.5 µs
B	Signal bandwidth	500.666 MHz
ΔR	Radar range resolution	0.3 m
R_u	Unambiguous range	100 m
M	Number of FMCW linear chirps	1052
N_{sym}	Number of OFDM symbols	1052
V_u	Unambiguous velocity	± 80 m s^{-1}
ΔV	Velocity resolution	0.15 m s^{-1}

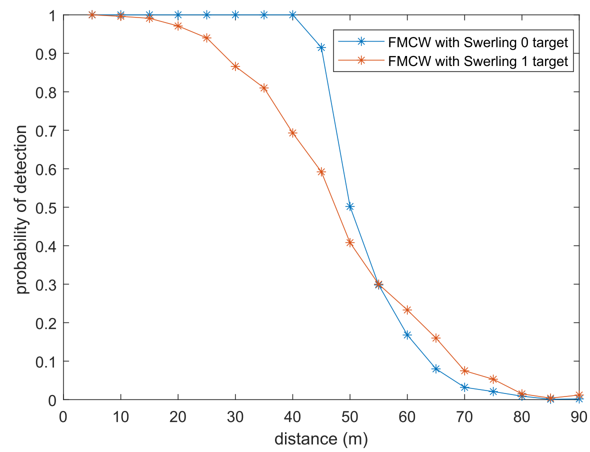

FIGURE 3. Detection probability for a Swerling 0 and a Swerling 1 target.

The detection probability is obtained after applying the Cell Averaging False Alarm Rate (CA-CFAR) algorithm based on [22] with a constant probability of false alarm (PFA) of 10^{-4} on the range/Doppler map. CA-CFAR threshold calculation is only valid for a Swerling 1 or 2 fluctuating target (exponentially-distributed radar cross-section) and for white Gaussian noise [22]. However, to simplify our simulation, we decided to use a Swerling 0 target, meaning a constant radar cross-section (RCS) over all Monte-Carlo iterations.

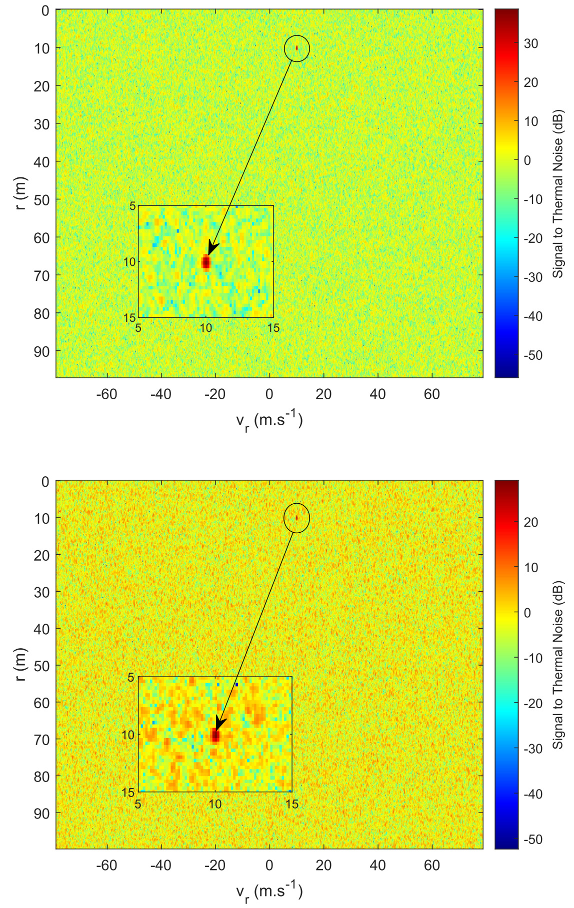

FIGURE 4. Top: FMCW range/Doppler map. Bottom: OFDM range/Doppler map.

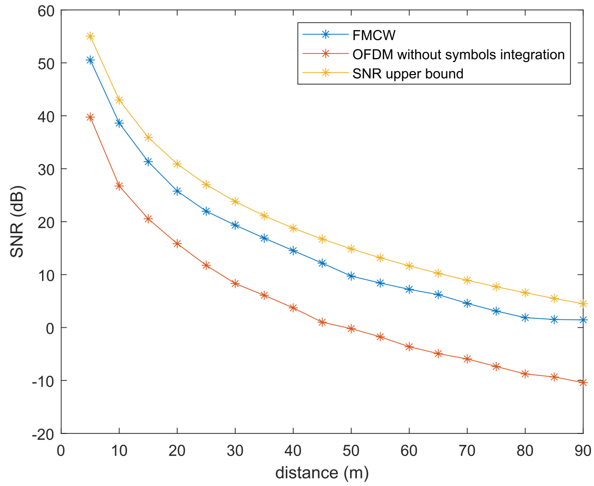

FIGURE 5. SNR vs distance for FMCW and OFDM.

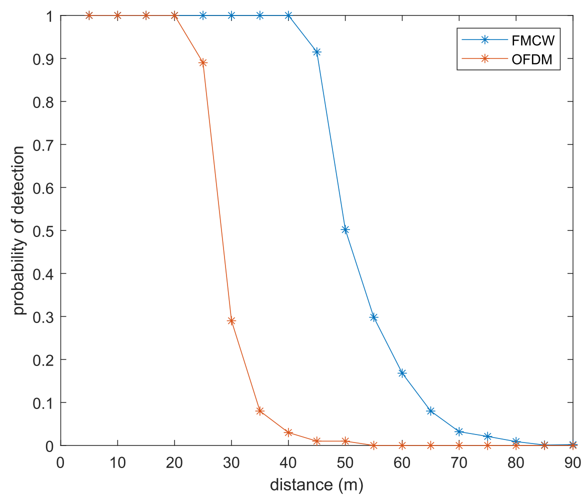

FIGURE 6. Detection probability vs distance for FMCW and OFDM radars.

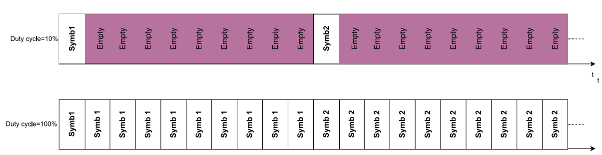

FIGURE 7. Symbols emitted for a simple OFDM signal with a duty cycle of 10% and symbols emitted for a coherent integration over symbols in reception of a OFDM signal with a duty cycle of 100%.

As shown in Fig. 3, the influence of this simplification on the detection probability is not significant.

B. PERFORMANCE WITHOUT COHERENT INTEGRATION

The main goal here is to determine the waveform offering the best detection performance. First of all, an example of range/Doppler map is depicted Fig. 4. It can be noted that targets can be clearly distinguished from noise in both cases. However, we have a 10 dB degradation of the SNR for OFDM radar compared to FMCW radar. To point out this difference, the graph of SNR versus distance for the two waveforms is plotted in Fig. 5 and compared to the theoretical value obtained from the radar equation. As mentionned before, the target is supposed to have a constant RCS of 10 m^2 and a velocity of 10 $m\,s^{-1}$. Here we simply consider a free space channel with a 0.4 dB/km attenuation.

As it can be seen on Fig. 5 when making comparison between the SNR upper bound, which is the theoretical maximum value of the SNR obtained from the radar equation [22], and SNR obtained by simulation, there are processing losses for both waveforms. These losses are more pronounced for OFDM radar not only because range and Doppler compression are less effective than for FMCW, but also because the value of the OFDM radar duty cycle is quite low at 0.1. Therefore, FMCW radar performs better in terms of SNR than OFDM radar. Figure 6 depicted the probability of detecting a target with a FMCW waveform and with an OFDM one. It shows that FMCW radar has a higher probability of detection compared to OFDM radar. It is so important to review the processing technique and the parameters used to perform OFDM radar, particularly the duty cycle, in order to have at least the same performance as FMCW radar.

C. PERFORMANCE WITH COHERENT INTEGRATION

To improve the SNR for OFDM, we implemented a coherent integration technique consisting in averaging received

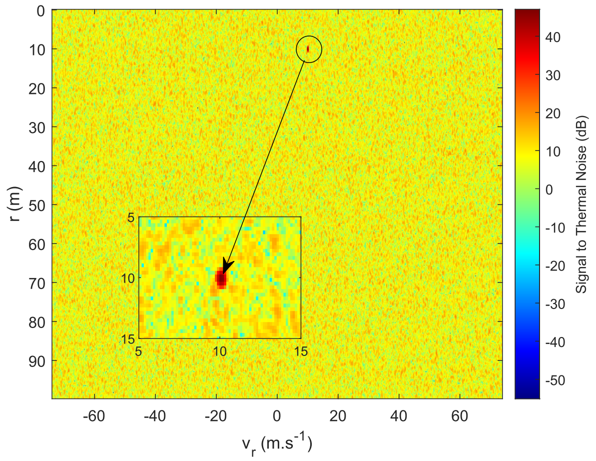

FIGURE 8. Range/Doppler map for an OFDM radar with coherent symbols integration at reception.

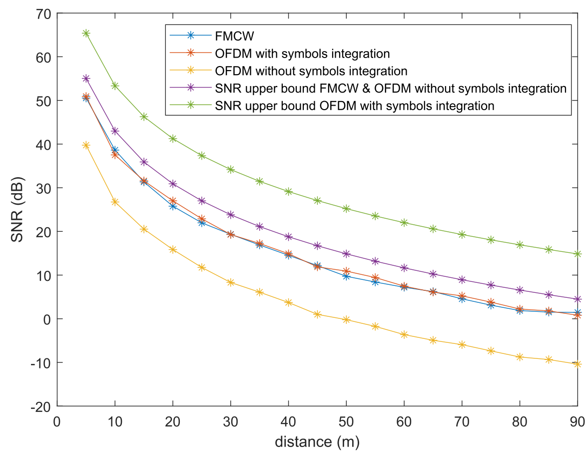

FIGURE 9. SNR vs distance for FMCW and OFDM with symbols integration compared to OFDM without symbols integration.

complex symbols, after removing the payload and before performing the 2D IDFT. It was decided to perform a 10-symbol integration in order to set the duty cycle of the waveform to 1. This duty cycle value, which is the same as FMCW duty cycle one, will improve significantly the energy efficiency of the OFDM waveform. The same symbol is thus repeated ten times in transmission before sending next symbol, resulting in $N_{sym} = 10520$. The principle is described Fig. 7.

Figure 8 shows the significant improvement of the target SNR with respect to Fig. 4. We have not only a high value of SNR but also a high noise level. The SNR value is around 40 dB, which is equal to FMCW radar for the same value of distance and velocity resolutions. As it is shown in Fig. 9, symbols integration improve considerably the SNR of OFDM radar. We obtained better values than conventional OFDM radar and same performance as FMCW radar. This amelioration can be explained by the increase in the number of symbols by a factor k, where k represents the number of integrated occurrences. It can be seen that the processing losses are as high as in the case without accumulation and still worse than those of FMCW radar.

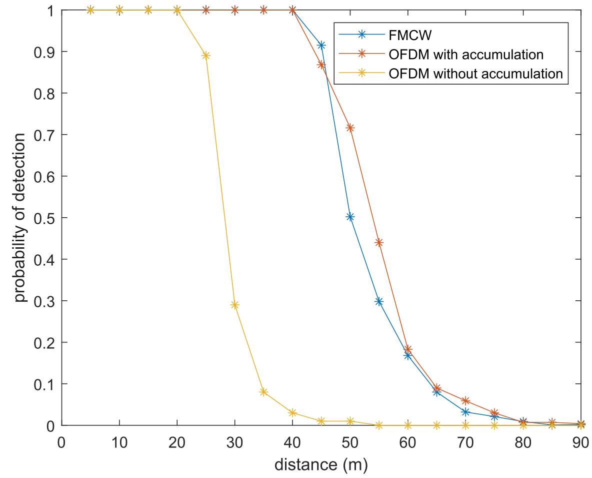

FIGURE 10. Detection probability vs distance for FMCW radar and OFDM radar with coherent integration compared to OFDM without coherent integration.

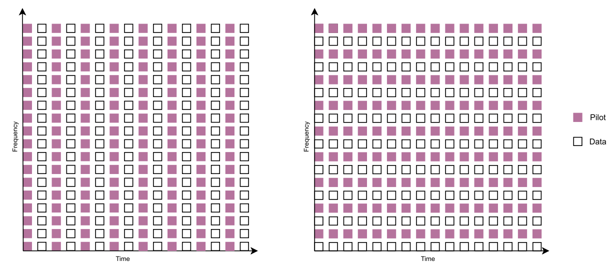

FIGURE 11. Left: block type arrangement. Right: comb type arrangement.

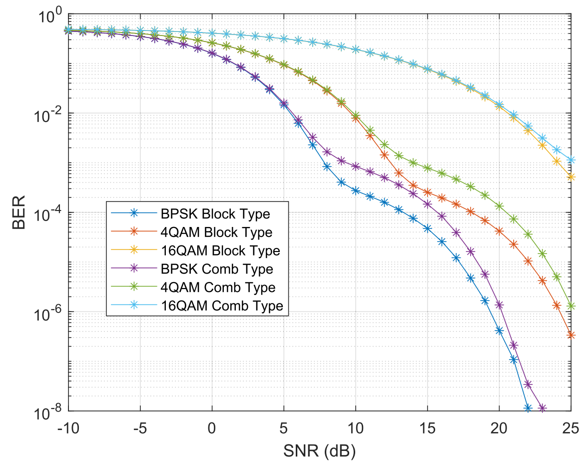

FIGURE 12. BER vs SNR.

The plot of the detection probability Fig. 10 shows that the detection performance along the distance is the same for both OFDM with symbols integration and FMCW radars.

V. COMMUNICATION ASPECTS

In this section, we provide simulation results of the BER for different number of pilots, type of pilots arrangement and different modulation constellations. We discuss then on the communication requirements based on the same parameters used by automotive OFDM radar without accumulation.

For channel propagation, additive white Gaussian noise (AWGN) and Doppler effect are considered. For the channel

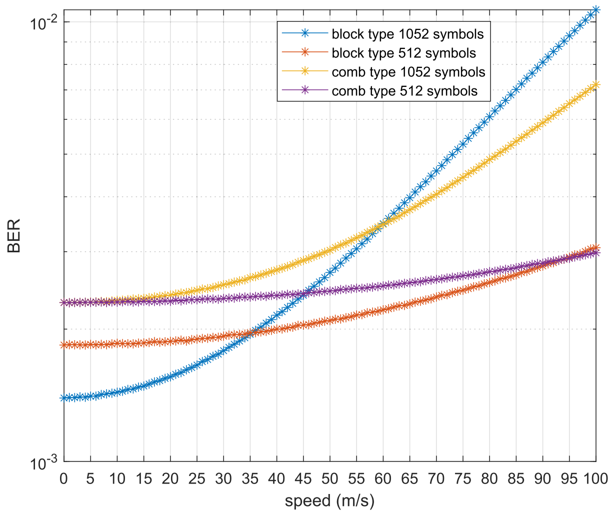

FIGURE 13. BER vs speed.

estimation, two pilots arrangement are chosen here as depicted in Fig. 11. For the comb type, pilots are inserted periodically in the frequency domain. We set, for a good estimation purpose, 1 pilot between 2 subcarriers, resulting in 167 pilots by symbols. The block type arrangement consists of periodic pilots in the time domain [23]. In this configuration, some entire symbols are used as pilots. Here we used one pilot every other symbol to perform the estimation. After selecting a pilot arrangement, we can then perform the channel estimation using an estimation method. In this paper, we will use the Least Squares estimation method [23] since it is easier to set up. It consists in interpolating in time or frequency the received signal to estimate the channel at the data symbols or subcarriers symbols. Our study considered low level pilots estimation method and did not use equalizer to observe communication performances.

Figure 12 shows the variation of the BER with respect to the SNR at 10 $\mathrm{m\,s^{-1}}$. It outlines the effect of modulation methods and pilots arrangement on the BER. Block type arrangement and comb type arrangement show the same evolution at this speed, with this propagation channel and for all the digital modulation methods used. The effect will be more visible under a vehicular communication channel and the most suitable pilots arrangement will be chosen.

Figure 13 shows the BER variation according to the speed. The relative speed is varying from 0 to 160 $\mathrm{m\,s^{-1}}$, inducing a Doppler shift from 0 to 40.56 kHz, for a SNR value of 12 dB. According to the different curves, the system seems to be robust against Doppler shift since we obtained low values of BER. The robustness could be due to the high subcarrier spacing of approximately 1.5 MHz that is much larger than the maximum subcarrier spacing available for current 5G OFDM, 240 kHz. The system becomes less robust as the speed goes up and the number of symbols or the coherent processing interval increases. The effect of the type of pilot arrangement used is more pronounced on these graphs. Considering the block type arrangement and at 80 $\mathrm{m\,s^{-1}}$, which is the maximum unambiguous velocity set for radar detection, we obtain a BER of 5×10^{-3} and 1.5×10^{-3} for 1052 and 512 symbols respectively. Taking 1052 and 512 symbols and based on the radar parameters above-mentioned, we obtain velocity resolutions of 0.15 $\mathrm{m\,s^{-1}}$ and 0.31 $\mathrm{m\,s^{-1}}$ respectively. That means that a low number of symbols deteriorate radar performance, especially in terms of velocity resolution but improves BER values.

The different BER curves show that a large number of symbols could degrade it. However, even if we send a huge number of symbols for coherent integration, each symbol is repeated a number of times, which could help to improve the reliability of the communication data. This hypothesis needs to be tested in further studies and a trade-off between the communication rate and the BER should be found to ensure a good cooperation between radar and communication.

In addition to the BER, the parameters chosen to perform OFDM radar could impact the communication data rate. The configuration of the waveform leads to a maximum data rate of 13,36 Mbps for a Binary phase-shift keying (BPSK) modulation using the comb type arrangement with half of the subcarriers used as pilots. We would go up to a data rate of 80.16 Mbps for a 64-QAM in the same configuration. Decreasing the subcarrier spacing, yielding a higher number of subcarriers, could increase considerably the maximum data rate to multigigabit as required for future V2X expectations [4]. For instance, a 120 kHz subcarrier spacing, which is the maximum subcarrier spacing for C-V2X at mmWave bands [24], leads to a maximum data rate of 8.3 Gbps for a 64-QAM. However, as mentioned in Section IV, the minimum subcarrier spacing required for our application is 405.6 kHz. In addition, the chosen 1499 kHz subcarrier spacing meets the requirements of current automotive radars but restricts the theoretical performance of communication. Nevertheless, since this subcarrier spacing is too large, it is necessary to find a trade-off between radar constraints and communication requirements in order to improve the data rate without degrading the radar performance.

VI. CONCLUSION

In this article, we compared FMCW and OFDM radars using current automotive radar parameters and the possible consequences of these parameters on communication in a joint radar communication. For this purpose, we took the parameters of a current mid-range automotive corner FMCW radar and applied them to the OFDM waveform. The simulations performed showed that OFDM waveform gives a lower SNR than FMCW for a similar target and a lower detection probability. To overcome this situation, we implemented a coherent integration of symbols on receive. This improved considerably the SNR and the detection probability up to that of FMCW. The BER has also been investigated using the same parameters than radar OFDM without accumulation. We observed that the system seems to be robust against Doppler shift. As our objective was to achieve the current performance of FMCW radars, the parameters defined are not those of OFDM currently used in communications. However, additional simulations using different propagation channels and experiments must be performed to ensure the actual robustness of the system. We intend to proposing a relevant technique for spectrum allocation between both systems for our future work

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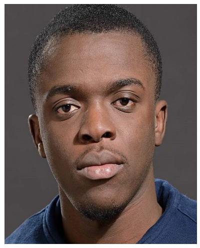

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