FMCW-Interference of Frequency Agile OFDM Radars

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Abstract—Flawless operation even with a high density of radar sensors in the vicinity is an essential prerequisite for radar sensors in automotive applications, safety systems, future autonomous driving, and in industry applications. Recent research shows the great potential of digitally modulated radars such as orthogonal frequency-division multiplexing (OFDM). Furthermore, novel frequency agile OFDM approaches such as stepped and sparse OFDM are superior to standard OFDM as they are able to achieve high resolution beyond the hardware-related band limits. In order to prevent possible mutual interference issues of common and novel modulation schemes, the influence of a state-of-the-art FMCW on stepped and sparse OFDM is examined in this paper. The effects of interference are investigated theoretically and through measurements using an experimental OFDM setup at 76 GHz and scenarios with up to two FMCW interferers. To prevent signal deterioration and limited detection performance due to interference, an efficient but low-cost detection and mitigation approach is presented for each of the two approaches.

Keywords—OFDM, FMCW, interference, radar, automotive, signal processing, compressed sensing.

I. INTRODUCTION

It is expected that the number of sensors in traffic will increase due to the rising demand for radar-sensor based automotive comfort and safety systems. Nevertheless, a faultless and reliable functionality of the sensors must be guaranteed. As the sensors have to share a common small frequency band, interference is likely and might decrease the performance of the sensors and the corresponding system [1]–[3]. Today, the majority of the sensors use frequency-modulated continuous waves (FMCW). However, recently, novel digital radar waveforms such as orthogonal frequency-division multiplexing (OFDM) [4] receive increasing attention in this field as well. Moreover, bandwidth optimized approaches such as stepped [5] and sparse OFDM [6] offer the possibility to overcome the bandwidth limitations of the system caused by the affordable hardware on both the transmitter and receiver, which has so far significantly limited the achievable resolution of the radar.

In the field of interference of OFDM radars, profound knowledge is still small. In [7], time domain blanking and signal estimation is proposed for impulsive noise in broadcasting OFDM. Slow-ramp FMCW interference for an automotive OFDM radar is investigated in [8], where frequency domain interference detection and signal recovery using linear prediction is proposed. Using measurements of state-of-the-art FMCW radar interference in an OFDM signal, in [9], a

frequency domain interference detection and simple mitigation method via signal leveling is presented. In [10], the mutual interference of OFDM radars is investigated.

In this paper, the impact of interference on sparse and stepped OFDM, referred to as thinned OFDM in the following, in comparison to standard OFDM is investigated using measurements at 76 GHz. Additionally, the question whether these approaches could possibly be more robust against a disturbance due to their special transmission pattern is examined more closely, and a suitable detection and mitigation method is presented.

II. THINNED OFDM RADAR

Similar to standard OFDM, the digital thinned OFDM transmit signal frame is composed of M OFDM symbols of duration T and $N_{\max}$ orthogonal subcarriers with spacing $\Delta f = 1/T$. The resulting bandwidth $W_{\max}$ must not exceed the limitations determined by the available digital-to-analog (DA) conversion rate. On each subcarrier of each OFDM symbol, a complex valued data symbol drawn from a modulation alphabet (e.g., QPSK) is transmitted. The generation of such a multi-carrier signal in time domain is achieved by an inverse discrete Fourier transform (IDFT) of the complex valued transmit data. Before DA conversion, the OFDM symbols are extended by a cyclic prefix and serialized.

Assume that the aimed channel bandwidth of the overall signal frame should cover $W > W_{\max}$, which corresponds to $N > N_{\max}$ theoretical subcarriers. The available signal is thus reduced by a factor $\gamma = W_{\max}/W$ in both bandwidth and subcarriers compared to the aimed channel. This is where the sparse or stepped OFDM approach comes in. Different than for standard OFDM, an agile carrier frequency is used, which can be adjusted for each OFDM symbol individually.

For stepped OFDM, the carrier frequency is increased periodically after every OFDM symbol ($m=1, \dots, M$) by $W_{\max}$ which gives $f_m = f_c + (m \bmod B)W_{\max}$, where $B = \lfloor 1/\gamma \rfloor$. Thereby a signal frame with a sawtooth transmission pattern of B steps and desired channel bandwidth W is generated.

By changing the carrier frequency randomly after any number $1, \dots, M_{\max}$ of OFDM symbols, the sparse OFDM transmission is achieved which also allows any frequency $f_m = f_c + b\Delta f$ with $b=0, 1, \dots, (N - N_{\max} - 1)$. By limiting the length of each signal sub-block (subsequent OFDM symbols on the same carrier) to $M_{\max} \ll M$, a sufficient degree of random subsampling of the aimed channel frame is achieved.

Similar to standard OFDM processing, the received signal of each OFDM symbol is down-converted to baseband using its individual carrier frequency, sampled, decomposed into its spectral components via a DFT, and then the modulation is reversed using an element-wise complex division. The resulting representation is referred to as the frequency domain. Conveniently, the samples of the discrete subcarriers and OFDM symbols are arranged in a matrix of size $M \times N_{\max}$. It has been shown in [5], [6], that this matrix can be increased to the actual channel frame size $M \times N$ by shifting each transmitted signal block or step to its corresponding relative position in the channel and filling all empty elements of the matrix with zeros. Afterwards, the range-velocity (r - v) evaluation is carried out using a 2D-(I)DFT, which yields the resolution as defined by the channel bandwidth W . As for sparse OFDM random signal blocks are used, this processing might lead to artifacts in the r - v -image. Hence, the 2D-(I)DFT processing is replaced by a 2D-compressed sensing evaluation using a complex approximate message passing (CAMP) algorithm [11] that is extended to 2D similar to [6].

III. EVALUATION OF THINNED OFDM IN PRESENCE OF FMCW INTERFERENCE

In presence of interference, a superposition of the desired OFDM signal and the interfering signal within the observed frequency band is received. In Fig. 1, time and frequency domain excerpts of stepped, sparse, and standard OFDM measurements in presence of an FMCW interferer are presented. For the OFDM radar, the experimental radar setup from [5] is used with carrier frequency set to 76 GHz and an equivalent isotropically radiated power (EIRP) of 8.5 dBm. The equivalent standard OFDM frame consists of $M=3072$ symbols and $N=2048$ subcarriers with a spacing of 500 MHz, which yields a total signal bandwidth of $W=1.024$ GHz and a symbol duration of $T=2\mu\text{s}$. The cyclic prefix duration is $0.5\mu\text{s}$. For the stepped and sparse measurements, the baseband bandwidth is reduced by a factor $\gamma=0.25$ (4 steps), which equals $N_{\max}=512$ subcarriers and $W_{\max}=256$ MHz. The FMCW radar interferer operates also at 76 GHz and exhibits a bandwidth of 2 GHz with an up-ramp time of $89.92\mu\text{s}$ and a ramp repetition time of $T_{\text{rtr}}=119.92\mu\text{s}$. Its EIRP is approximately 17 dBm which is almost three times that of OFDM. This difference of radiated power is noticeable in Fig. 1. Due to the block-like signal structure of thinned OFDM, the FMCW signal not continuously interferes with the OFDM signal. In addition, the FMCW signal is compressed into only some subcarriers in the frequency domain, as the FMCW ramp passes only a bandwidth of some Δf during one symbol.

The measured scenario comprises three stationary targets at distances 4.25 m, 5.6 m, and 6.1 m and up to two interferer. The corresponding r - v -images of the signals in Fig. 1 are shown in Fig. 2 (right) along with an interference-free measurements using the identical transmit signals (left).

Without interference, for both standard and stepped OFDM an SNR of about 43 dB is achieved, for sparse OFDM it is about 10 dB more due to the additional pseudo-SNR that

is generated by the 2D-CAMP post-processing [6]. In case of interference, a distinct decrease of SNR is observable for all approaches. Through the 2D-(I)DFT processing, the interference signal gets decorrelated and its power is spread approximately equally in the r - v -image. This power dominates over the inherent OFDM system noise power and thus reduces the achieved dynamic. Furthermore, since in all measurements the same number of ramps was collected, the percentage of disturbed samples of all available samples in frequency domain is approximately similar ($\approx 1.67\%$). The thinned approaches are therefore generally neither superior nor inferior to the standard approach in terms of susceptibility to FMCW interference. This is also explained by the circumstances that sparse OFDM imitates random sampling of the channel while stepped OFDM performs a linear subsampling of each subcarrier. However, generating a subset randomly or linearly from elements of a certain distribution results eventually in the identical distribution in this subset. For stepped OFDM, streaky artifacts are recognizable. They are caused by the periodical interference of the same step in about the same frequency range every twelfth step repetition, as observable in Fig. 1.

IV. INTERFERENCE DETECTION FOR THINNED OFDM

A straightforward but yet effective method for interference detection and allocation for standard OFDM is power detection via thresholding in frequency domain [8]–[10]. As thinned OFDM uses a block-like signal pattern, detection approaches that require local amplitude information of neighboring samples as in [8], [9] are prone to errors.

Here, a more robust global threshold based on the expected OFDM signal magnitude in frequency domain is proposed. Since the magnitudes are Rayleigh-distributed, an estimate using the available discrete samples offers $\hat{\sigma} = \text{median}(|\mathbf{Y}|) / \sqrt{\ln(2)}$, which equals the modus of the distribution where the matrix $\mathbf{Y} \in \mathbb{C}^{M \times N_{\max}}$ contains all available nonzero samples. As long as at least 50% of these samples are not affected by interference, this provides a robust approximation. In case of frequency variant signal magnitudes due to non-ideal components in the receiver, the signal must be calibrated prior to this.

A threshold $\tau = \kappa \hat{\sigma}$ is obtained by introducing a scaling factor κ . This factor controls the sensitivity of the detection and thereby the number of correct detections or true positives (TP) of interfered samples versus false detections or false positives (FP) of non-interfered samples. For ideal detection TP should be maximized and FP should be minimized. Heuristical investigations revealed that $\kappa=3$ is a good choice. For all conducted measurements using two interferer separately and simultaneously, in Fig. 3, the detected relative interference $p_{\text{meas}}^f = P_{\text{det}} / (M N_{\max})$ is compared to the theoretical relative interference $\hat{p}^f = W_{\text{int}} / (\gamma W) \cdot T / T_{\text{rtr}}$ where W_{int} is the shared bandwidth of FMCW and OFDM. The second interferer (FMCW II) has similar configurations as FMCW I except of an up-ramp time of $50\mu\text{s}$ and a ramp repetition time of $60\mu\text{s}$. The red solid line marks the perfect detection. The dotted line shows the average ratio $p_{\text{meas}}^f / \hat{p}^f$. As the slope is steeper

Fig. 1. Excerpts of time (upper) and frequency (lower) domain of interfered measurements for (a) stepped, (b) sparse, and (c) standard OFDM. The presence of interference within the considered channel bandwidth is highlighted in time domain and the corresponding FMCW ramps are framed in frequency domain.

Fig. 2. r - v -Profiles and SNR of the measurements in Fig. 1 (right) in comparison to a measurement using the identical transmit signal but without interference (left) for (a) stepped, (b) sparse, and (c) standard OFDM.

than expected, the approach tends to FPs. Yet, in case of no interference, the amount of FPs is only 0.06% for stepped, 0.07% for sparse, and 0.01% for standard OFDM.

Significant is the high variance of points for stepped OFDM in Fig. 3a. This is caused by signal constellations

Fig. 3. Predicted ($\hat{p}^f$) versus detected (p_{meas}^f) relative interference for all measurements where either FMCW interferer I or II or both are active.

Fig. 4. Example of an unfavorable (left) and favorable (right) signal constellation in the channel for stepped OFDM ($\gamma=1/16$).

where the slopes of the steps and the frequency ramp are approximately similar and is even more pronounced when their repetition times are a multiple of each other. In Fig. 4 two measurements with $\gamma=1/16$ (16 steps) is shown where the ramps and steps show a disproportionately high (left) and low (right) degree of overlap.

V. INTERFERENCE COUNTERMEASURES

Since for FMCW interference the relative expected and detected interference is very small in the frequency domain, it is proposed to simply remove interfered samples from the OFDM signal by zeroing before applying a 2D-(I)DFT. In this case, if all interfered samples have been entirely removed, the remaining signal degeneration is solely a result of the decreased processing gain and probably emerging

Fig. 5. Recovered r - v -images and SNR of the interfered measurements in Fig. 2 for (a) stepped and (b) sparse OFDM using zeroing.

artifacts due to the introduced signal gaps. However, since $p_{\text{meas}}^f \leq 20\%$ even for fast(er) FMCW radars and multiple interferer, the remaining decrease of SNR is less than 2 dB. Moreover, as only a few subsequent elements along both frequency and symbol dimension are removed, no considerable artifacts are generated. Therefore, and taking into account the computing effort, zeroing is sufficient and an additional signal reconstruction is not considered necessary and reasonable in this case. For sparse OFDM, the zeroed samples are merged with the a-priori signal gaps such that both are restored during signal recovery which will additionally recover the processing gain. Hence, zeroing of corrupted samples offers a low cost, fast, and almost perfect recovery of the r - v -image for frequency agile thinned OFDM.

In Fig. 5, the recovered r - v -images for the interfered measurements in Fig. 2 are shown. In all cases a similar SNR as in the non-interfered measurements is achieved. Additionally, in Fig. 6, the achieved range profiles are shown.

VI. CONCLUSION

The impact of FMCW on frequency agile stepped and sparse OFDM is investigated and experimentally validated using measurements at 76 to 77 GHz. In case of interference, the SNR of the radar image is decreased significantly for both approaches due to the additional receive power that is decorrelated during processing. A robust method of detecting interfered samples via thresholding in frequency domain is presented. For interference mitigation, zeroing of interfered samples in frequency domain is proposed for both stepped and sparse OFDM. For sparse OFDM, it is also possible to include these zeroed samples in the normal signal recovery and thus restore them as well. Through the proposed interference detection and mitigation, approximately the same SNR as in an interference-free measurements is achievable.

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Fig. 6. Comparison of the range profiles of measurements with and without interference before and after interference elimination.

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