Joint OFDM for Radar and Communication

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***Abstract*—The increasing congestion of the radio wave spectrum through the exponentially growing need for wireless communication, combined with the move of communication channels in Radio Detection And Ranging (RADAR) spectrum, lead to the idea of Joint RADAR and Communications (JRC) systems. This paper explores the current state of JRC systems using Orthogonal Frequency Division Multiplexing (OFDM) in the literature. The paper first gives an overview of the concept of OFDM and its basics, an introduction to RADAR systems and the mathematical background of the target detection and tracking with RADAR, followed by the basics of JRC systems and is concluded by a discussion of the currently proposed implementations of JRC systems.**

***Index Terms*—sensing, hight-speed networks, OFDM, RADAR, RadCom, OFDM RADAR, waveform design, FMCW, overview**

1. Introduction

With the increasing demand for wireless communication in the last decades and in the future, the spectrum has and will become more crowded. On top of this, the need for higher transmission speeds means the trend of using higher and higher frequencies, traditionally occupied by Radio Detection And Ranging (RADAR) systems, will continue. This overlap of bandwidth results in in-band and adjacent-band interference creating problems for both applications. [1], [2] Those interferences pose a problem for the communication and military industry but also the aviation, car and space industries due to using RADAR in their respective applications. To solve this problem, the idea of integrating RADAR and communication in one system has surfaced as Joint RADAR and Communications (JRC) or RADAR and Communications (RadCom) system. This integration is possible due to the use of similar components and the move to digital signal processing in both fields. Those components include transmitting and receiving antennas and the signal creation and processing logic. This integration reduces the cost and needed space of the system by reducing the number of components needed but increases the complexity of the JRC system. [3]

2. Frequency multipexing

Multiplexing is a technique that combines multiple signals to one to send over a shared channel to optimize the channel for a chosen criteria, such as data rate. There is a multitude of categories the technique can assigned to, e.g Time Division Multiplexing (TDM), Space Division Multiplexing (SDM), Frequency Division Multiplexing (FDM) and Code Division Multiplexing (CDM). [4] This paper focuses on FDM and its special form Orthogonal Frequency Division Multiplexing (OFDM) due to its advantages in Joint RADAR and Communications (JRC)-systems.

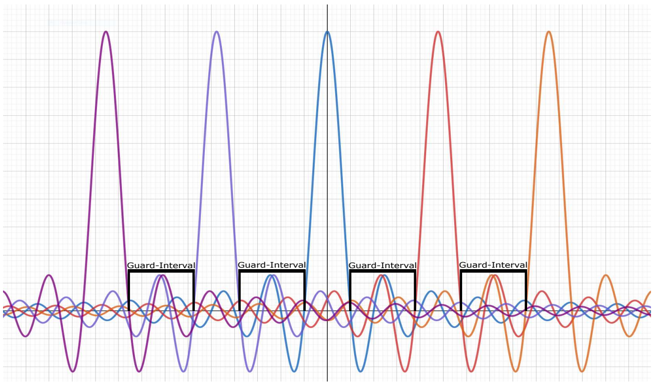

Figure 1: **Diagram in frequency-amplitude-domain of a FDM channel with 5 subbands modulated with rect-functions on. Resulting in 5 $sinc$ functions with $sinc(x) = \frac{\sin(x)}{x}$ with their respective peaks at the carrier-frequencies they are modulated on. The subbands are spaced apart by a guard interval spacing, but there are still Inner Symbol Interference (INSI) between the subbands due to the sidelobes of the $sinc$-functions not being zero at the peaks of the other $sinc$-functions.**

2.1. Frequency Division Multiplexing

FDM is a technique that divides a channel into multiple none overlapping frequency bands called subbands, which are spaced apart by a guard interval spacing (guard band) as seen in Fig. 1. The subbands have an individual carrier-frequency in the bandwidth of the original channel. A different data stream is modulated on each sub-carrier, e.g. by multiplying the carrier frequency with a sequence of rect-functions representing the bits of the data stream. With the rect-function being defined, in dependency of τ, the duration of the signal being at 1, as:

$$\mathrm{rect}(t) = \begin{cases} 1 & \text{if } |t| \leq \frac{\tau}{2} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

The subbands are combined to one signal via an Inverse Fast Fourier Transform (IFFT) and transmitted over the channel to the receiver. The receiver splits the signal

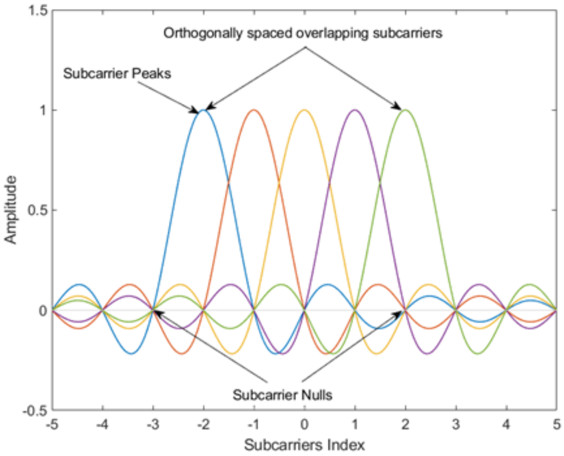

Figure 2: **Diagram in frequency-amplitude-domain of an OFDM channel with 5 subbands modulated with rect-function on. Resulting in 5 $sinc$-functions with peaks at the carrier-frequencies in the frequency-amplitude domain. The subbands are orthogonal, i.e., each maximum amplitude corresponds to the minimum absolute amplitude of the others, by choosing the subcarriers spacing $\delta f = \frac{1}{\tau}$ with τ the length of the window in the rect-function.** [9]

into the subbands with a bandpass filter and demodulates the data streams. [5], [6] The advantages of FDM are the more efficient use of the available bandwidth, no time synchronization is needed and the low complexity of implementations. The disadvantages are the limited number of subbands, the difficulty in assigning the frequencies to the subbands and the INSI between subbands. The INSI stems from the sidelobes of the $sinc$-function not being zero at the peaks of all the other functions. Therefore, adding or subtracting from the combined amplitude of the signal at that frequency. [7] To overcome these disadvantages, OFDM was developed.

2.2. Orthogonal Frequency Division Multiplexing

OFDM is a digital modulation form of FDM in which the subbands are orthogonal to each other. This means the adjacent sub-carriers do not interfere with each other because the maximum power of each sub-carrier corresponds directly to the minimum power of all the other sub-carriers as seen in Fig. 2. [8] This orthogonality is archived by using sine (or cosine) waves with frequencies of $k \cdot \Delta f$ with $k \in \mathbb{Z}$ and $\Delta f = \frac{1}{\tau}$, where τ is the window length of the rect-function.

Through this, the distance between two adjacent carrier frequencies can be controlled by choosing a fitting τ and the need for guard-bands is eliminated. Therefore, higher spectral efficiency is archived compared to FDM. However, due to multipath propagation and the possibility of dispersion in the frequency domain, most OFDM systems use a Cyclic Prefix (CP) to reduce the ISI as seen in Fig. 3. The CP is a part of the signal that is repeated at the beginning of the next signal and is used to compensate for the delay of the channel. The length of the CP is chosen to be longer than the maximum delay of the channel. The receiver removes the CP, and the signal is processed as if it was not delayed. [10]

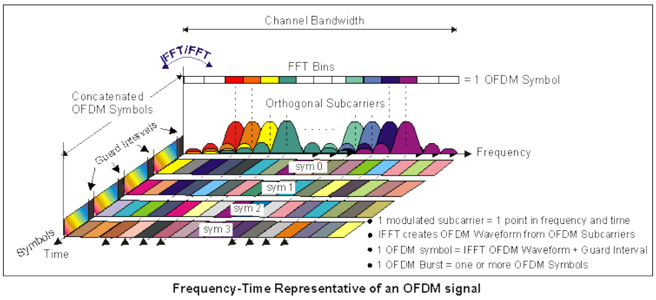

Figure 3: **Diagram in frequency-amplitude-time-domain of an OFDM channel with 8 orthogonal subbands modulated with rect-function on combined to OFDM-symbols. Between the OFDM-symbols in the time domain guard interval are inserted to reduce Inter Symbol Interference (ISI)**. [11]

The carrier-frequencies have data streams with a certin maximum length modulated onto, are then combined into one signal via an IFFT. This OFDM symbol is transmitted over the channel to the receiver. The receiver then uses a Fast Fourier Transform (FFT) to split the signal into the sub-carriers and demodulates the data streams. [11] The advantages of OFDM are the high spectral efficiency, resistance to multipath propagation and no ISI. OFDM comes at the cost of increasing the complexity of the implementation.

3. Radio Detection and Ranging

This section gives an overview of the basics of Radio Detection And Ranging (RADAR) systems and the calculations needed to determine the angle, distance and velocity of a target. It also gives an overview of the different types of RADAR systems and their waveforms.

3.1. Basics of RADAR

A RADAR system uses electromagnetic waves in the frequency range of 3MHz to 100GHz to detect targets in its range. A pulse, the transmitted pulse (TP), is transmitted via an antenna and the echo, the received pulse (RP), is processed to determine the target's angle, distance and angular velocity. The RP can vary from the TP in frequency and amplitude. The components of a RADAR system vary, but all have at least one oscillator to create the TP, one or multiple antennas and a logic to process the RP. If only one antenna is used for transmission and receiving, a RADAR system is called monostatic, quasi-monostatic if transmitting and receiving antennas are close to one another and bistatic if the antennas are at different locations from the target's viewpoint. On top of the angle, range, and velocity sensing functions, RADAR systems can also detect the size of the target, shape, material and moving parts. However, the complexity of RADAR systems and their cost and size increase with the number of functions they can perform. [12]

RADAR waveforms. There are two basic options for a waveform when designing a RADAR system: a Continuous Wave (CW) or a pulse. With a CW RADAR system, the TP is a constant wave, and the receiver is continuously active. Therefore, the RP can only be separated from the current TP through a frequency change induced by the movement of the transmitter, target or receiver (Doppler shift), mixing the CW with the received signal or via spatial separation of transmitter and receiver. The pulse RADAR transmits a pulse and then waits for the echo. Both intervals together are called Pulse Repetition Interval (PRI). [12], [13]

Classification of RADAR systems. RADAR systems can be classified in different ways. One way is to classify them by the way they transmit the TP. This can be done by classifying them in CW and pulse RADAR systems. Another way is to classify them by the amount of transmit and receive antennas, if there are multiple receive antennas and one transmit antenna the system is called Single Input Multiple Output (SIMO) and when there are multiple transmit and receive antennas Multiple Input Multiple Output (MIMO). [13]

3.2. The RADAR equation

Every signal transmitted from an antenna or received by one is damped by a certain factor, depending on the used antenna. This is the result of its gain. Every antenna has a specific amount of gain G, that is its radiation efficiency η multiplied by the directivity D. As a result, the power of the RP depends on the power of the signal before transmission, the gain, the wavelength and the distance to the target and its RADAR-cross-section. The equation to determine this power is given by $P_r = \frac{P_s G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4}$ with P_r denoting the power of the RP in W, P_s the power of the original signal in W, G_t the gain of the transmitting and G_r the gain of the receiving antenna, σ the RADAR-cross-section of the target in m^2, λ the wavelength of the TP and R the distance to the target. The RADAR-cross-section is the area of the target TP illuminates. It can be reduced by using RADAR-wave dampening materials or with an optimized shape, e.g. fewer 90-degree angles. The power is also dampened by the distance to the target with a factor of the distance to the power of four due to the quadratic dampening of the TP over the one-way distance. Due to the dampening of the TP by multiple factors, the echo of a target might be too weak that its Signal to Noise Ratio (SNR) is so low that the echo is not distinguishable from the noise, making it undetectable. To combat this, the signal is filtered with filters matched to the TP and possibly integrated between pulses (adding up the magnitudes from multiple echoes) increasing the SNR, if the PRI is small enough that the target has only moved a negligible distance. [12]

Clutter detection and suppression. Clutter is any unwanted signal echo that is not from a target, e.g. the echo of a rock face or a bird. The simplest way to detect clutter is by comparing the RP to the RPs of previous cycles. If the echo is similar to the echoes in RPs of previous cycles with similar range, angle and velocity in relation to the movement of the RADAR system during the cycles, the echo is considered clutter. It is also possible to use the staticity of most clutter to detect it. To suppress detected clutter, its echo in the RP can be ignored, or the average of previous echoes can be subtracted from the current echo, and the threshold for target detection can be raised resulting in fewer false positives.

3.3. Range detection

To estimate the distance to a target, the time between the transmission of the TP and the reception of the RP is needed. As a result, CW RADAR needs to assign the echo to an earlier point in time to determine the range. This can be archieved via frequency modulation, e.g. increasing the frequency of the TP with time and dropping back to the base frequency after a certain time t_c. This interval is called a chirp, and the system is called Frequency Modulated Continuous Wave (FMCW) RADAR. The range formula for (quasi-)monostatic PRI systems is $R_t = \frac{cT_R}{2}$, with c being the speed of light, R_t the distance between the transmitter and the target and T_R the time between transmitting the pulse and receiving it the round trip time which can be measured. In contrast, bistatic RADAR PRI systems need a synchronization element to determine the delay. This can be done via a reference channel if the distance between transmitter and receiver is known. The range formula for bistatic systems is $R_t + R_r = cT_R$, with R_t and R_r being the distance between the transmitter and the target and the receiver and the target. The noise and interference in real-world applications adds some ambiguity to the range detection. Furthermore, if the range exceeds the maximum unambiguous range $R_{maxu} = \frac{c \cdot PRI}{2}$ [14] the target seems to be closer than it is. This is called range ambiguity. A target might not be detected at all due to overlapping echoes. This occurs when there are multiple targets in the same direction and with a distance smaller than the range resolution R_{res}. For pulse RADAR systems the $R_{res} = \frac{c \cdot PRI}{2}$ [15] and for FMCW systems the $R_{res} = \frac{c}{2B} T_c f_s$ [16], with B being the bandwidth of the FMCW, T_c the duration of the cycle and f_s the sampling rate.

3.4. Radial velocity detection

As mentioned before, the RP will be shifted in the frequency domain through any distance change between transmitter and target, and target and receiver. This Doppler shift will be positive if the distance is decreasing and be negative if it is increasing. If the Doppler shift induced by the target is known, the radial velocity of the target can be calculated with $v_r = \frac{f_d \lambda}{2}$. If it is unknown, it can be estimated with the range of the target at multiple pulses. For a target moving faster than the maximum unambiguous Doppler velocity $v_{max} = \frac{\lambda}{4 \cdot PRI}$ an exact velocity can not be calculated. On top of that, when the target is moving at the radial velocity of $n \cdot v_{blind} = \frac{\lambda}{2 \cdot PRI}$ with n being an integer or f_d being an integer multiple of $\frac{1}{PRI}$, the target appears not to be moving at all. This is called blind speed. [12], [17]

3.5. Angle detection

With an isotropic antenna, i.e., the antenna emits equally in all directions, only the range and velocity of the target can be detected. This can be resolved by using a directional antenna and moving the antenna in azimuth (horizontally) and elevation (vertically) mechanically or by using beamforming. Thus, the angle of the target can be estimated to be in the direction of the transmit beam. Better accuracy of angle detection can be archieved by using multiple receive antennas spaced apart by $d_r = \frac{1}{2}\lambda$. Those receive the same signal, but through the space between them, the signal travels an additional distance of $d_r \sin\theta$. This results in a phase shift (see Fig. 4). This phase shift ω has to be measured so the angle of arrival θ can be calculated with $\theta = \sin^{-1}\left(\frac{\omega\lambda}{2\pi d_r}\right)$. Due

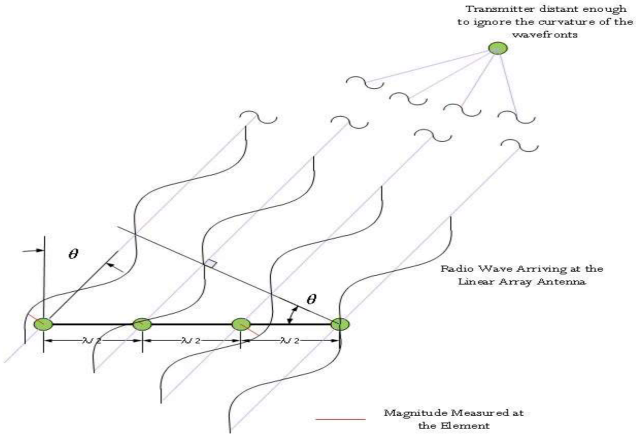

Figure 4: **Schematic of a RADAR system with 4 receiving antenna spaced apart $\frac{\lambda}{2}$ with λ being the wavelength. The received wavefront appears linear through the distance to the source at the angle θ. This angle results in a different time of arrival and therefore with a shifted phase.** [18]

to the fact that ω can only be estimated in the range of $(-\pi, \pi)$, the unambiguous Field Of View (FOV) is limited to $\theta_{fov} = \pm \sin^{-1}\left(\frac{\lambda}{2d_r}\right)$. If more antennas are used ω can be estimated more reliable, and a FFT can be performed on the signal sequence. The peaks of the result indicate the angle of arrival. Increasing the number of receiving antennas N_r leads to sharper peaks, thus higher accuracy. If the antennas are spaced apart by the distance d_r the angle resolution is $\theta_{res} = \frac{2}{N}$ with $N = N_t \cdot N_r$, if the transmitting antennas are spaced apart by the distance $d_t = N_r \cdot d_r$. This positioning allows the detection of N_t different transmission, which increases the sensing capabilities of the RADAR system. [13]

4. RADAR and communication systems

JRC or RADAR and Communications (RadCom) systems combine RADAR and communication systems. The idea of JRC systems is to share the components of the RADAR, such as transmitting and receiving antennas, signal generators and signal processing logic. JRC systems also have the upside of sharing information between the subsystems, which can be used to enhance both, e.g. by using the RADAR to detect communication partners and using beamforming to increase the range and SNR of the communication system. The targets are to reduce the interference between the RADAR and communication system, cost and space. There are two main approaches to JRC systems, the first is to use the TP of the RADAR to send data to a communication partner and to detect targets in one pulse. The second approach is to switch between the TP for radar and for communication dynamically, depending on the need for communication. Of course, FMCW JRC systems can be used, but the transfer rates are currently not high enough. A combination of the two is feasible but loses the ability to sense continuously, as well as other downsides. [16]

Possible applications. There are many areas that could profit from JRC systems. The two focus points are intelligent transport systems, e.g. self driving cars or adaptive cruise control, and the military. JRC systems could enable cars to communicate with each other about their properties like position, speed and predicted route and with infrastructure like traffic lights or sensors in the road through protocols like Vehicle to Everything (V2X). This should be archivable, while not making the car dependent on market penetration, making it more reliable and secure by its sensing capabilities and attractive to car manufacturers. The military could use JRC systems to detect and track targets and to communicate with allied assets and command centers while reducing the cost of acquisition space and power needed for two separate systems. [19]

Waveform. Designing a wave that satisfies prerequisites for both RADAR and communication is the main challenge of JRC systems. Stand-alone RADAR systems use waves specifically designed for a high autocorrelation, i.e., the similarity between the wave at one time and at a later point in time. [20] Using regular RADAR waves would result in orders of magnitude lower symbol rates compared to a communication system in the same bandwidth. One option to decrease the need for autocorrelation in a wave, is using multicarrier waveforms such as OFDM. Those also solve the problem of the low transfer rates of normal RADAR waves. Additionally to the need for a specific autocorrelation and bit rate, there might be other requirements for the wave, such as certain sensing capabilities, a low Bit Error Rate (BER), low probability of being detected or increased resistance to jamming. All those properties need to be considered when designing a JRC waveform. OFDM has many of the most commonly needed properties, such as a high bit rate, resistance to multipath fading, low BER and cost of implementation, due to its extensive use in communication systems and the resulting availability and low cost of components. [19]

5. Current State of RadCom Systems

The current state of JRC systems is mainly theoretical, with only prototypes and simulations created to prove some of the proposed concepts. This is because the JRC systems are still in the research phase and are not yet ready for commercial use. This section will give an overview of current proven implementations of JRC systems in scientific papers. The primary focus lies in designing the waveform, as it is the main challenge of JRC systems. This, combined with the different demands of the use cases, results in many propositions for waveform designs for JRC systems. However, due to the need for a high data rate in most RadCom systems, a particular focus is put on OFDM-based waveforms, as they are known to achieve high data rates.

Shared OFDM subchannels. One of the more unique suggested solutions is using precoded OFDM symbols in a MIMO RADAR system. The precoder is designed to minimize a specific sensing-communication metric and can be used for beamforming. On top of that, the OFDM subchannels are divided into two groups, private and shared. A sub-carrier is shared when all transmitting antennas in the RADAR system can transmit on it, enabling high data transmission rates. The parallel transmission on the same sub-carrier leads to the carriers losing their orthogonality and creates coupling between the transmitted symbols.

The loss of orthogonality complicates the estimation of the target properties by preventing the formation of a virtual array. The number of private sub-carriers and the assignment to a transmission antenna to increase the accuracy of the RADAR system is dynamically decided on, depending on the situation. The private sub-carrier can be used to create a virtual array and for pilot transmission for channel estimation, but they decrease the archivable transfer rates. [1]

Non-contiguous OFDM subbands. Another proposition is to use non-contiguous OFDM subbands for data transmission located in a large spectrum for sensing. However, using regular OFDM waves has the downside, of a high Peak to Average Power Ratio (PAPR) resulting in lower amplifier efficiency, and in-band and out-of-band distortion. To combat this, the sensing bands need to transmit waves with good autocorrelation, optimized with a unique algorithm to decrease the PAPR of the entire spectrum. [21]

Downsides of OFDM-based waveforms. The downsides of OFDM-based waveform are mainly the same as normal OFDM has, combined with the high PAPR. However, the main disadvantage of OFDM-based waveforms in JRC systems is the reduction of SNR compared to traditional RADAR systems, resulting in lower accuracy of the target parameters estimations, probability of detection and higher BER. This effect can be reversed to within a margin by transmitting the OFDM symbol multiple times until the next symbol and using specific pilot symbol patterns and modulation schemes to decrease the BER. However, the sending of symbols continuously makes currently widely used access patterns like Carrier Sense Multiple Access (CSMA) harder to implement. [16]

6. Conclusion and future work

This paper has given an overview of the basics of FDM, OFDM, RADAR and JRC, and the current state of RadCom systems. It shows that OFDM is a good candidate for RadCom systems due to its high data rates and the possibility of a low PAPR. However, the use of OFDM in RadCom systems is not without downsides. The use of normal OFDM in RadCom systems does not reach the possible maximum transmission rates. To reach these rates, extra steps in the signal creation and processing are needed. Overall, we believe that OFDM is the best candidate for a JRC waveform due to the availability and low cost of components and their for JRC systems' favorable properties. In the future, more research has to be done in the field of RadCom waveform design, their implementation, robustness to jamming, multipath fading and beamforming. Furthermore, protocols might be needed for the communication part of the JRC system as some propositions are making it impossible to use currently widely used access control protocols.

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