Idea*: DFT-S reduces PAPR and allows for more inexpensive receivers to be used. Since MIMO uses many antennas, each with their own receiver, then MIMO + DFT-S could lead to a much more substantial cost savings

Stepped_carrier_OFDM_dps_higher_resolution: increases the overall baseband bandwidth, and therefore the resolution in the range-doppler map
Corr_radar_dsp: computation of cross-correlation function is computationally taxing; the idea of a two-stage approximation or estimation is employed: this reduces the complexity considerably, and facilitates the use of the FFT and IFFT algorithms in the calculation.
JCAS_for_6G: Joint communication and sensing for everyday IoT devices, and 6G networks

Conference papers:
- Recap and summary up the top; I'd aim to have 3-4 references in here.
- A description of what will be discussed, a layout of the paper.
- What are the **assumptions** made; what is the setup…

Paper titles are shown in green

Maximum LIkelihood Speed and Distance Estimation for OFDM Radar:
- Solving the expression that results from the MLE study *analytically* is *very tough*… instead, by using quantisation, the FFT and IFFT algorithms can be used.
- Since the signal power is 1 (due to normalisation), then the SNR is *really just* the noise power:
  $10\log_{10}(\sigma^2)$

- SNR = (P_{rx})/(Noise power) = $(P_{rx})/(k_B T B * NF)$
- Making the lengths of the FFTs and IFFTs longer than the dimensions of the frame can *improve* the accuracy of the estimation when the SNR is high as well (meaning our signal is quite a bit *stronger* than the noise…)
- $G = T_G/T$
- m_0 and n_0 are the ***true*** values of the indexes n and m. As SNR decreases, the estimation of m_0 and n_0 becomes harder…
- Quantization error can be reduced via padding… by increasing the size of the FFT and IFFT calculations…

Key Assumptions:
- The entries of F_{Tx} are **uncorrelated**.
- The modulation system is **normalised to unit power**; this will always be the case for constant-modulus *alphabets* such as PSK (only the phase changes, the amplitude or *modulus* remains constant)
- In defining ***F***, the noise matrix ***W*** is altered
- Noise power is defined by **thermal noise** plus a **noise figure**…
- $N_{max} = GN_{FFT}$; $M_{max} = DM_{FFT}$

Parametrization of Joint OFDM-based Radar and Communication Systems for Vehicular Applications:

- Vehicles are equipped with mobile communication systems in order to exchange information about the current traffic conditions, current events related to the traffic flow, as well as information and entertainment systems… Cars communicating on the highway/motorway is more and more likely as time goes on…
- IEEE 802.11p is the dominating standard (most commonly used in the developed world) for vehicle-to-vehicle communication…
- IEEE 802.11p is *closely related to* the 802.11a standard…
- The number of subcarriers N, the subcarrier spacing Δf, and the guard interval T_G, are *all* important design parameters…
- Δf must be smaller than the coherence bandwidth of the channel (the bandwidth over which the channel can be assumed to be constant)...
- $\Delta f = 10B_D$ (where B_D is the *Doppler spread*…)... this condition is crucial, as it protects against the deorthogonalization…
- The Doppler spread: the difference between the largest and smallest occurring Doppler shifts…
- Mobile Txs and Rxs are limited in their power consumption; this *effectively* imposes a minimum SNR for effective operation (if the SNR drops below some threshold, the accuracy of the calculations is lost…)
- From Free-Space Path Loss model:

  $P_{Rx} = I(A_{eff.})$, where I is the intensity due to the source at a distance d…

  $I = (P_{Tx})/(4\pi d)^2$

  $A_{eff.} = \lambda^2/4\pi$
- Distance or range resolution is:

  $\Delta d = c/(2N\Delta f)$

  $N\Delta f$ represents the bandwidth of the OFDM system; the smaller the resolution the better. With this in mind, it seems like increasing the bandwidth of the OFDM system is favourable if we want a good resolution. This can be done by either increasing N, the number of subcarriers, *or* by increasing the subcarrier spacing…

- The author uses T_F, which I think means the time for one OFDM frame. I think this based on the equation he gives for T_F:

  $T_F = M(T + T_G)$ // The part inside the brackets is the OFDM symbol time.

  The above equation for T_F is equal to the time duration of sending all M OFDM symbols… so T_F must be the *time to send an OFDM Frame…* *I just see now that the author mentions it as being the frame duration…

- If the frame duration is much longer than the channel coherence time, then the *equaliser* needs to be adjusted often (so that it can effectively do its job)
- For a fixed bandwidth (i.e., imagine we must operate at a fixed bandwidth), increasing the subcarrier spacing too much seems to have a negative effect on the *symbol* rate…

- A good choice for the subcarrier spacing Δf is that value which maximises the symbol rate (and therefore the data rate)...
- The symbol energy per noise power density is:

  $E_s/N_0 = P_R/(N\Delta f N_0)$

- It seems that it's good to include a "Conclusion" in a conference paper.

Key Assumptions:
- The Δf **subcarrier spacing** or **subcarrier distance** must be much smaller than the **coherence bandwidth** (B_C) of the channel - that is, the **frequency span** over which the channel can be assumed to be constant…
- Δf must be **a lot wider** than the ***Doppler spread*** $\mathbf{B_D}$…

Doppler Tolerance of OFDM-coded Radar Signals:
- The authors mention that the message transmitted within the OFDM radar signal is *buffered*, so as to allow **correlation** to be performed in the receiving part of the radar…
- The authors use *noc* to represent the ***number of frequency carriers***… This is interesting, and shows that there doesn't need to be one, **strict** variable naming convention… once you explain what each letter is representing at the beginning, confusion should be avoided…
- The authors use **exp(x)** instead of $\boldsymbol{e^x}$… this could be for a variety of reasons… maybe they were using a different editor; maybe less space of lines are used when one goes with **exp(x)** over $\boldsymbol{e^x}$…

OFDM Radar Algorithms in Mobile Communication Networks:

Drawbacks of periodogram-based approaches:
- The quantisation errors when using the formulas for the *time delay* and *Doppler shift*… These **errors** mean **more post processing** is needed to be done…

  There are **two principal ways** to combat the **quantisation noise** and **errors**:
  (1) Use a **finer mesh**, meaning *increase* N_{Per} and M_{Per}; this results in **more computations**, as the **FFT** and **IFFT** sizes are now bigger. The benefit, however, is that **less post processing** is needed.
  (2) Find a way to **locally maximise** $L(F|\theta)$ near the estimates of *n* and *m*… most likely involves **interpolation**, meaning **more post processing**…

- Drawbacks of the **cross-correlation** approach are (as mentioned in M. Braun's paper):
  (1) The increased computational complexity. Why? Because the efficient FFT-based algorithm used to compute the **periodogram** can not be **as effectively applied** when computing the **2D cross-correlation**.
  (2) The **lower** peak-to-spur ratio. *The increased spur levels are caused by the structure of the transmitted data, which cause additional peaks in the auto-correlation function of the time domain OFDM signal*. Algorithms have

been developed to remove these spurs [38], but this only **increases the computational cost**.

(3) The author (M. Braun) concludes that the cross-correlation method does not make **efficient use** of the **OFDM signal structure**…

Comparison of Correlation-based OFDM Radar Receivers:

Summary:

- Benefits of combining the radar and communication would be:
    (1) Easier hardware integration
    (2) Saving in other ways, such as **weight**, **volume**, and **energy**…
- As also is pointed out, OFDM relies on low-complexity transmitters that use FFTs and IFFTs. OFDM is also robust against the channel's frequency selectivity…
- Pilot tones and Cyclic prefixes are unconventional for radar, and maybe not needed if an OFDM system is to switch to radar functionality…
- There can be disturbances in a **Range-Doppler** map which are **caused by the data symbols**… known as ***Random sidelobe*** or ***Pedestal***…
- Passive radars or radar systems are ones in which the radar **processes** reflections that are coming **off objects** that are not active, or cooperating in the radar process…
- **Bistatic radar**: a system in which the transmitter and receiver **are separated** by a distance… whereas **Monostatic** is when the transmitter and receiver are in the same location (co-located)
- Three aspects of performance are analysed:
    (1) Computational complexity
    (2) SINR
    (3) Resilience to ground clutter
- This conference or presentation paper (or article… it is longer than the conference papers I've read so far) declares all labels or notations at the beginning for clarity… this *might* be a good idea:

> *Notation:* We use $\mathbf{Z}$ for the set of integers. $\mathcal{I}_N$ and $\bar{\mathcal{I}}_N$ denote the finite sets $\{0, \ldots, N-1\}$ and $\{-N, \ldots, -1\}$, respectively, and $\setminus$ the set difference. $\mathbb{E}\{\cdot\}$ is the expectation operator, $\|\cdot\|$ the ℓ_2-norm, and sgn is the *signum* function anywhere but in 0 where we set $\mathrm{sgn}(0) \triangleq 1$. The so-called Dirichlet kernel is defined as
>
> $$\mathcal{D}_N(u) \triangleq \frac{1}{N}\sum_{n=0}^{N-1} e^{j2\pi \frac{n}{N} u}.$$

- When stating an equation from a different paper, the reference is being given **just before** the equation:

Provided that $K \gg 1$, the baseband expression of a transmitted OFDM frame critically sampled at rate B is, therefore, [28]

$$s[p] = \sum_{m=0}^{M-1} \left(\frac{1}{\sqrt{K}} \sum_{k=0}^{K-1} c_{k,m} e^{j2\pi \frac{k}{K}(p-mL)} \right) g[p-mL] \quad (1)$$

- You can reference **specific equations** in papers in a similar way to below:

Note that after proper synchronization and direct path removal, a similar signal model is obtained on the surveillance channel of a bistatic radar receiver (e.g., see [17, Eq. (5)]).

- Matched-filtering approach: uses the cross-correlation, and the equation given is:

$$\chi^{(r,s)}(l,\nu) \triangleq \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} \chi_m^{(r,s)}(l,\nu) e^{-j2\pi\nu m} \qquad (5)$$

- Proximate Matched Filter (PMF): Matched Filter (MF) is often approximated by **ignoring** the **phase rotation** due to the Doppler shift caused by the target. Also, the Matched Filter approach is **computationally heavy**…
- There are three main types of **Correlation-based receivers** studied:
  (1) Matched Filtering Approaches
  (2) Reciprocal Filtering Approaches
  (3) Hybrid Approaches

- This paper is heavily centred on the **ambiguity** function, which is based on the **auto-correlation** and **cross-correlation** functions:

Full name	Acronym	Notation
Matched filter	MF	$\chi^{(r,s)}$
Proximate matched filter	PMF	$\tilde{\chi}^{(r,s)}$

The *tilda* (~) over the letter “Chi” χ denotes the fact that it’s a **proximate** matched filter, and so it is an **estimate** of the true matched filter…
- The expression given for the matched filter approach is:

$$\chi^{(r,s)}(l,\nu) \triangleq \frac{1}{\sqrt{KM}} \sum_{p=0}^{LM-1} r[p] s^*[p-l] e^{-j2\pi\nu p/L}. \qquad (4)$$

I notice that the **form** of this **definition** is **very similar** to:

$$\chi(\tau, f_d) = \int_{-\infty}^{+\infty} s(t)s^*(t-\tau)e^{j2\pi f_d t}dt$$

If so, then ***p*** in the first equation maps to ***t*** in the second. As for why ***p*** (which as just mentioned is most likely representing discrete time) is going from **0** to **LM - 1**, I think it is because there are **M** OFDM symbols or "blocks", and **L** is the extended block length, which I think means the OFDM symbol length ***with*** the **CP** included:

and $L \triangleq K + \Delta$ is the extended block length, or indifferently, the pulse repetition interval. It is worth recalling that

So **LM** is *really* the total number of data symbols in each **OFDM Frame**.

- The paper then breaks **equation 4** up into the following:

$$\chi^{(r,s)}(l, \nu) \triangleq \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} \chi_m^{(r,s)}(l, \nu)e^{-j2\pi\nu m} \qquad (5)$$

where the function $\chi_m^{(r,s)}$ denotes the same cross-correlation, but this time computed over a single block m of the received signal r, i.e., over L samples

$$\chi_m^{(r,s)}(l, \nu) = \frac{1}{\sqrt{K}} \sum_{p=0}^{L-1} r[p+mL]s^*[p+mL-l]e^{-j2\pi\nu p/L}. \qquad (6)$$

- **Proximate Matched Filtering** is a way of implementing the Matched Filtering approach, but doing so with less computations… of course the result is not *perfect*, but the computational load is much better
- Proximate-Matched Filtering (PMF) reduces the computation complexity of the normal or standard Matched filtering approach. The PMF expression or equation can be **implemented** via the FFT
- There is also a discussion on PMF-CP, which is basically **applying** the PMF approach **after** you remove the **CP** from each **block** or **symbol** (*m*)
- Another tweak or slightly different algorithm is the PMF-CC, where the CC stands for **circular correlation**.

Reciprocal Filtering Approaches:

- The reciprocal approach is **quite close** to the **matched filtering** approach. The main difference is that the **replica** of the **transmitted signal** is replaced by the **complement** of **s**… this **now** conveys the sequence:

$1/c^*_{k,m}$ instead of $c_{k,m}$

> 2) The proximate reciprocal filter with circular correlation (PRF-CC), which was quite recently introduced in PBR under the acronyms MCC [25] and CHAD [26], actually corresponds to the so-called *symbol-based* processing proposed a few years earlier in the RadCom literature [24].
>
> The latter remark particularly emphasizes the need to unify the literature on OFDM radar, which is one of the purposes of this article.

- This method has a **good ability** to attenuate spurious peaks caused by signal periodicities such as **pilot tones** (discussed in ***DVB-T Passive Radar Signal Processing***)
- For unit-variance (unit-amplitude) alphabets, there is no difference between **reciprocal filtering** and **matched filtering**…

Performance Comparison:

- The **two main metrics** for the performance of the **various** filters **are:**
    (1) Computationally complex
    (2) SINR

> Again, for simplicity, but without loss of generality, we assume in what follows that the Doppler dimension is also critically sampled (i.e., ν is of the form $\nu = n/M$ with $n \in \mathcal{I}_M$), and that the target is perfectly on-grid with $n_0 \triangleq f_D M \in \mathcal{I}_M$ denoting its Doppler bin index. We recall that we suppose $M \gg 1$ to ignore the effects of the truncation of r by the radar receivers.

- When **unit-variance** modulation schemes are used then the **reciprocal** and **matched** filtering approaches are **equivalent**.
- It seems from this paper that **if** the **target** is **stationary** then **attempting** to compensate for the **non** existing **Doppler phase** within each **block** seems to be **detrimental** for the MF approach.

  "Especially, since the target is static here, attempting to compensate the nonexistent rotating Doppler phase within each block even seems to be detrimental for the MF, as hinted by Fig. 1(b)"

DVB-T Passive Radar Signal Processing:

- The paper states that **implementing** a **discrete** version of:

$$\chi(\tau, f_d) = \int_{-\infty}^{+\infty} s(t)s^*(t-\tau)e^{j2\pi f_d t}dt$$

Matched filtering
Is **computationally expensive**…

- The typical two stage pulse-Doppler approximations for OFDM discard or remove the cyclic prefix first.

Ambiguity Analysis For OFDM Radar Signals:

Signal Processing for Passive Radar Using OFDM Waveforms:

- MUSIC **algorithm** is used as a **2D** spectral estimator (in tandem with **spatial smoothing**)
- New concept of **compressed sensing** is used to **identify** targets
- As this paper points out, **if** the **transmitted** signals used in the **radar** process are **not known** then implementing a **matched filter** is made much harder…
- One **promising** aspect of **MIMO** radar waveforms is that each **transmitter** can transmit **independent** waveforms; it also allows for **spatial diversity**, which could lead to **higher** target position **resolution**…
- As the paper suggests, some of the **data symbols** can be deactivated (i.e., some of the **subcarriers** can be left unused). This might help in **protecting** the bandwidth edges, as well as in estimating the **Doppler shift**.
- The text below is very good (I must say, as academic papers go, this one is a little easier to read, and more clear):

C. Matched Filter Receiver

The standard approach is to "search" for targets using a bank of correlators tuned to the waveform given a certain Doppler shift and delay, i.e., a matched filter. As an example, the kth correlator will produce for every $\hat{\tau}$ and a fixed Doppler shift $\hat{a}_k f_c$

$$z_k(\hat{\tau}) = \int_0^{T_i} e^{-j2\pi\hat{a}_k f_c t} x^*(t-\hat{\tau})y(t)dt. \quad (6)$$

The above expression, although using different variable names, is the **same** or has the **same form** as those that I have seen in other papers.

Evaluation of The Ambiguity Function for Passive Radar with OFDM Transmissions:

- Reducing the **floor** of the ambiguity surface is preferable**.** This is because as the floor increases, **signal** returns from **weaker** targets are masked and not picked up by the radar receiver. As the floor (or bottom) of the surface increases, the **dynamic range** of the receiver decreases, which is not desired.
- The **orthogonality** of the subcarriers used in OFDM can be exploited or used to **zero** the ambiguity surface's floor at **low delays**.

- This paper considers **non-unit** amplitude modulation **alphabets**… unlike most others
- The **DIM** (**Data-Independent Approach**) (where there is no modification made to the data symbols c_{jk}) leads to **worse** results when compared with the **MCC** approach (**modified processing** with **circular correlation**) or **MLL** (**modified processing** with **linear correlation**)

PAPR reduction of BF-OFDM waveform using DFT-Spread technique:

(1) OFDM signal has a high PAPR
(2) OFDM with CP has been adopted by 5G (we knew this already)
(3) OFDM schemes have **poor frequency localisation** - this is due to the use of the rectangular pulse-shaping filter
(4) Null subcarriers are used at the edge of the spectrum to help prevent interference from other wireless systems. But this negatively impacts the **spectral efficiency** of the system…
(5) High PAPR can cause distortion when non-linear High-Power Amplifiers (HPAs) are used… this distortion can also lead to an increase in the bit error rate (BER)
(6) If a signal has "weak excursions" then its "envelope" is quite constant or non fluctuating…

Analysis of PAPR Reduction of DFT-SCFDMA System using Different Sub-carrier Mapping Schemes:

- Again, this paper mentions that one of the major drawbacks in the OFDM scheme is the non-linear distortion that can occur when the signal is passed through a high-power amplifier (HPA) during transmission…
- Other methods of reducing the PAPR:
    (1) Partial Transmit Sequence (PTS): this can be applied to minimise the PAPR to a certain level. But it is **spectrally inefficient**; this is probably not good for communication, but does it really matter when it comes to radar, where we are not interested in **bit rates/throughput** as much as in communications?
    (2) Selective Mapping (SLM). This is a probabilistic approach and also reduces the **spectral efficiency**… it will also make the system more complex. But again, does **spectral efficiency** matter so much when we are trying to identify targets etc. like in the radar application?

On Performance Limits of DFT Spread OFDM Systems:

- UE stands for User Equipment. We want the power consumption of User Equipment to be low. Hence, the high PAPR of OFDM transmission is undesirable for **uplink** transmission.
- For LTE 3G, the adopted **uplink** modulation scheme has been **DFT-Spread OFDM** (DFT SOFDM)
- In standard OFDM transmission, each sub-channel can be thought of as an AWGN channel, with an **SNR determined by** the receiver noise and **channel's response** at that sub-channel only. The same **cannot** be said about **DFT SOFDM**.
- Unitary Fourier Matrix:

  $$\mathbf{F}\mathbf{F}^H = \boldsymbol{I}$$

OFDM-Spread OFDM MIMO Radar - An Alternative for Reduced Crest Factors:

- Transmit signals have a **relatively high *crest factor***

- This requires **high-power** amplifiers (HPA) with **highly-linear characteristics**; these are **expensive**, and have a **high power consumption**
- Pre-spreading stage is investigated
- DFT-S-OFDM radar is "hardware friendly"
- OFDM waveform is **widely employed** in wireless communication systems
  (1) OFDM is robust against interference
  (2) The modulation and demodulation is done **efficiently** via IFFT and FFT operations
  (3) If the carrier spacing is sufficiently large, then the OFDM system is robust against Doppler shifts
  (4) In wireless communication, OFDM is often chosen due to its **high spectral efficiency**
- Many peak-to-average power ratio (PAPR) reduction techniques have been analysed in the literature. Such as Tone Injection (TI), Tone Reservation (TR), Selective Mapping (SLM)
- When the data rate requirement is lessened, the high PAPR aspect of OFDM may be combated by using Discrete Fourier Transform (DFT)-spread OFDM (DFT-s-OFDM)
- **DFT-s-OFDM** has been employed as an uplink modulation technique in fourth-generation **4G** mobile radio systems Long-Term Evolution (LTE)
- Since data rates don't matter so much in the pure radar case, the (PAPR) may be reduced considerably - this entails less expensive transmit high-power amplifiers;

Performance Verification of Symbol-based OFDM Radar Processing:

- When it comes to correlation-based radar receivers, random correlations in the transmit data can cause unwanted sidelobes in the radar image…
- This symbol-based approach eliminates the transmit data **before** performing the processing. This means the problem of random correlations is avoided. And sidelobes only result as artefacts of processing (e.g. FFT block at Rx)
- The transmit data is eliminated by using element-wise division…
- The result of the element-wise division (which is the Channel's frequency response H) is then subject to an IFFT operation. This yields the channel's impulse response $\{h_n\}$.
- Periodicity in the radar image occurs. The maximum distance corresponds to a time equal to one symbol duration (T). This means that this symbol-based approach is good for short-mid range applications
- The **processing gain** (gain or scaling of SNR at the receiver) is the same as that of the correlation-based approach…

Waveform design and signal processing aspect for fusion of wireless communications and radar sensing:

- Similarities in front-end architecture for wireless communications and radar systems. (they can **share hardware** components if both functions are shared)
- Carrier frequencies for communications systems have shifted closer to the microwave region, and are now of the same order of those used in radar
- ITS: V2V (vehicle-to-vehicle communication), and environment sensing
- Main challenge in combining the two is to find **a good waveform**
- For radar, classically, waveforms with **good or optimum** autocorrelation properties have been chosen. Examples include LFM pulse, also known as "chirps". **But the symbol rate relates to the chirp rate, which is typically *much lower* than the symbol rate achieved by a system dedicated solely to communication**

- A continuous-time transmit signal is **required**
- Performing a **scan** by rotating **narrow beam antennas** would be slow, and the update rate would be low… it also hinders the **communication coverage**
- Digital Beamforming (DBF): cover a **wider region** *and* focus on each spot in the region at the same time. Do this by **combining Rx signals from multiple Tx antennas**. Each antenna has a wide and dedicated region to cover; concept of MIMO or Smart Antennas - **goal: maximise SNR and data rate**
- Communications range goes down as f_c goes up, this is because the **free space loss increases**
- For orthogonality, spacing between subcarriers must be = 1/T
- DSP algorithms can function in the time or frequency domain
- Random correlations in the data (which *can* occur, especially if there is **a lot** of data being transmitted) can cause unwanted or misleading peaks in a Doppler-range map
- Correlation-based Rx can be computationally heavy or taxing
- Can produce Doppler ambiguities
- Author promotes the **direct** and **simple** *symbol-based approach*; it **eliminates** the transmit data **before processing**, and in this way avoid the problem of random correlations in the transmit data causing unwanted peaks in the Doppler-range map
- DBF and MIMO radar systems: **each receiving antenna** has a **dedicated receiver that** consists in **converting** to baseband and then performing **analog-to-digital conversion**.