Abstract—The first radar was patented 110 years ago. Fast forward to today, radar applications have become ubiquitous in typical applications i.e. speed control, air traffic control, airborne and space-borne missions, military applications and remote sensing. Research for medical radar applications is also progressing well for breast cancer detection and tumor localization. Automotive radar for safety and autonomous driving are meanwhile being produced in millions per year. Despite the significant technological advancements the radar system technology unfortunately did not evolve like the communications and other related technologies for the last 20 years. With the development of high-speed electronic devices and higher demand for radar systems, the current state-of-the-art radar system concepts will undergo a revolution. They will be conceptualized and integrated in the current radar technologies leading to revolutionary radar systems. This will ultimately lead to new radar features and radar signal processing.

Keywords—Future Radar; MIMO Radar; Digital Beamforming; Array Imaging

I. INTRODUCTION

The first radar was patented in 1904 by Christian Hülsmeyer [1]. It was a pulsed radar, radiating differentiated video pulses, generated by a spark gap. Hülsmeyer’s ideas were based on the experiments by Heinrich Hertz in 1888, when Hertz detected the polarization dependent reflection of electromagnetic waves. Since then the radar system technology and signal processing have significantly been improved for the state-of-the-art radars at their time, for example, the 1938 Pulse Radar Patent of Colonel W. R. Blair. The first electronically scanning radar was the German Search Radar FuMG 41/42 Mammut-1 in 1944. Numerous innovations in radar system technology followed since then, e.g. the FMCW radar technology. In the same way the radar hardware technology and the radar signal processing have advanced significantly. Until 1990 the radar technology has always been a little ahead of the communications technology. But with the advent of the wide spread mobile communications, this situation changed. Although radars became equipped with new semiconductor devices and signal processing technologies, the system-level radar concepts have remained the same since many years; these radars still

- transmit the identical signal for their whole life
- transmit only one frequency at a time (e.g. FMCW)
- ‘see’ only a small area at a time (e.g. Phased Array)
- scan mechanically (e.g. airport radar)

Most of the current state-of-the-art radars, except for some military radars, transmit an identical signal for the whole time of their operation. Functionality-wise, this is inefficient since the radar will be limited to a narrow field of operation, when there are many different tasks/scenario that are encountered even for a single radar, e.g. near range-far range, tracking, low range resolution-high range resolution, etc. Regarding military radars, the radiation of uncorrelated signals is a necessity to avoid interception/detection, else their countermeasures become straightforward.

The frequency spectrum became the most valuable resource in the world since 20 years ago, because it is strictly limited and is not transferable. As such it must be used as efficiently as possible. Technologies that exploit the spectrum for opportunistic spectrum usage i.e. cognitive radio, or dual combination systems i.e. radar-communication systems, are already being extensively researched to take full advantage of the limited spectrum.

Since the year 2000, the number of radars being used is rapidly increasing. The fastest growing market for radar applications is the automotive radar. Within a few years there will be foreseeable millions of radars on the roads, with many cars equipped with up to five different radars systems. Consequently there will be a selective inoperability in these radar systems due to strong inter-system interferences. Interference within the same frequency band can be avoided if the radar signals are properly coded and are continuously changing for low cross-correlation, like in communications.

For scanning radars, the conventional method is still to use a narrow beam, scanning either mechanically or electronically (i.e. phased arrays). This approach of scanning a wide area for target detection is highly inefficient. Mechanical scanning is cheap but slow; the phased array method is faster but expensive. In both cases only one beamwidth area is scanned at a time.

The drawbacks of conventional radars mentioned above and some other deficiencies of the current state-of-the-art radars must be overcome in the next ten years. The potential strategies for future radar system concepts will include:

- intelligent signal coding, e.g. OFDM, CDMA
- MIMO Radar - multiple transmit and receive antennas
- digital beamforming for a higher angular resolution with wide coverage without mechanical moving parts
- array imaging - efficient systems of reduced size and cost
- combination of radar-communication = RadCom
These new system technologies will cause a revolution in radar system concepts. In addition to the technical features, these will also allow the cost reduction of the systems, increase the efficiency and the development of smart radars.

In the following sections these points will be explained in more detail and summarized from the point of view of communications and other well-known technologies.

II. RADAR SIGNAL CODING

A. Radar Signal Coding Requirements

The basic requirement for future radars is to cover time and spectrum simultaneously, with each transmitted signal differently coded. This allows, as will be shown later, the compression of the received signal in the dimensions of time and frequency thus increasing the compression gain significantly up to 50 dB - 70 dB. This in turn allows the reduction of the transmit power due to the additional compression gain. For small radars e.g. automotive radars, this increases their power efficiency. For military applications the detectability of these radar signals for localization and countermeasures becomes much more difficult, because they are similar to communications signals.

From communications several different coding schemes are known e.g. CDMA (Code Division Multiple Access), DSSS (Direct Sequence Spread Spectrum), OFDM (Orthogonal Frequency Division Multiplexing) among others. For radar applications the signal model selection must be made according to (but not exclusively) [2], [3]:

• simplicity of signal generation
• good decorrelation of simultaneous and consecutive signals
• ease of signal compression
• simplicity of signal processing
• possibility to transmit information
• suitability for MIMO operation
• simplicity of hardware realization

This list is longer for special applications such as missile control or ground penetrating radars. There is no one solution for all scenario; hence in this paper the OFDM coding is selected, because it covers several of the above arguments, like simple realization, good de-correlation and simple processing.

B. OFDM Radar Signal Coding

The OFDM signal coding is well known from communications. The available and/or required spectrum is covered by multiple orthogonal subcarriers, which are all decorrelated due to their pulse duration \( T_0 \) being inverse to the subcarrier distance \( \Delta f \)

\[
\Delta f = \frac{1}{T_0}
\]

In Fig. 1 the OFDM carrier arrangement is shown. The decorrelation results from the overlapping of the peak of a particular subcarrier at the nulls of other subcarriers. A number of OFDM carrier modulations such as QAM and PSK can be used. Arbitrary information such as music or data can then be modulated onto the subcarriers. The spacing of the subcarriers is usually determined by the maximum expected Doppler shift \( f_{D,\text{max}} \). By the rule of thumb the subcarrier spacing should be more than 10 times the \( f_{D,\text{max}} \) to mitigate the effect of inter-carrier interference during the radar processing. The number of subcarriers \( N_C \) together with the subcarrier spacing \( \Delta f \) result in the available bandwidth \( B = N_C \Delta f \).

The total length of the transmit signal is composed of the number of carriers \( N_C \) and the number of consecutive symbols \( M_{\text{sym}} \) in time, which together form the transmit pulse. The transmitted signal simultaneously covers the whole bandwidth over the duration of the transmit signal, \( M_{\text{sym}} T_0 \). In Fig. 2 the transmitted ‘block’, as a matrix, is shown.
\[
x(t) = \sum_{m=0}^{M_{\text{sys}}-1} \sum_{n=0}^{N_{C}-1} D_{Tx}(mN_{C} + n) \exp(j2\pi n\Delta f t) \cdot \text{rect}\left(\frac{t-mT_0}{T_0}\right), \quad \text{with} \quad mT_0 \leq t \leq (m+1)T_0.
\]

The radar processing steps will be discussed in another section. It will be apparent then that the transmitted information influences the outcome of the radar processing if a direct correlation is used to extract the range and Doppler information. This can be circumvented by using the proposed radar processing with only Fourier transformation in [4]. As can be seen from Fig. 2, the total signal compression results from the compression in time domain multiplied by the ones in the frequency domain, which leads to the high compression gain mentioned earlier.

### III. Digital Beamforming

Radars illuminate an angular area defined by the horizontal beamwidth \(\psi_{3\text{dB}}\) and the vertical beamwidth \(\theta_{3\text{dB}}\) at a time. For operation over wider angular areas some sort of scanning either mechanically or electronically (i.e. beam switching or a phased array switching) is required. Conventional analog methods limit the effectiveness of scanning radars. A solution to this is Digital Beamforming (DBF). The basic idea of DBF is to transmit/receive multiple independent weighted beams formed by an array of antenna elements. The received multiple signals by each receive antenna element are then down converted for A/D conversion and stored in a memory. From this memory these multiple beams can be digitally processed simultaneously by a proper shift of phase and amplitude weight \(w_i\) conversion correlation. The major advantage is that the signals are available for processing, not limited by the pulse duration, and that the whole antenna element beam coverage can be simultaneously processed with multiple beams. The angular resolution is however still determined by the receive antenna beamwidth. Fig. 3 shows the principle of the received signal processing.

![Fig. 3. The principle of digital beamforming.](image)

In the following the DBF technique is shown in more detail in Fig. 4. The single antenna elements receive the incoming wave with a phase \(\phi\) resulting from their position in the array and the direction of the incoming wave \(\psi_i\). The angular distortion \(\Delta \phi = \sin(\psi_i 2\pi d/\lambda)\) is a function of the relative element spacing and the wave incident direction. The beam vector for a single impinging wave is:

\[
\vec{b}(\psi_i) = \begin{bmatrix} e^{j0\Delta \psi} & e^{j1\Delta \psi} & e^{j2\Delta \psi} & \ldots & e^{j(N-1)\Delta \psi} \end{bmatrix}
\]

The processing of the direction of the incoming wave is then simple Fourier transformation, because the phases increase linearly. For multiple beams a beam vector is set up for each direction and these are then combined to a beam matrix \(B\), as shown in equation (4).

\[
B = \begin{bmatrix} \vec{b}(\psi_1) & \ldots & \vec{b}(\psi_i) & \ldots & \vec{b}(\psi_l) \end{bmatrix}
\]

The DBF method can also be extended for a 2D scenario as shown in Fig. 5.

![Fig. 4. Antenna element phase delay for a beam vector wave \(\psi_i\).](image)

![Fig. 5. 2D digital Beamforming for a 2D antenna array with an incoming wave at \(\psi_i, \theta_i\).](image)

For the 2D array to form the beam vector \(\vec{b}_i(\theta_i, \psi_i)\) the element phase shifts become:
\[
\Delta \phi_x = 2\pi \frac{d_x}{\lambda} \cos \theta_i \\
\Delta \phi_y = 2\pi \frac{d_y}{\lambda} \sin \psi_i 
\]  

(5)

The beam vector is then the Kronecker product of these phase shifts. The processing again is a Fourier transformation in the two angular directions, where the multiple beams, in the angular ranges covered by the single elements, can be processed simultaneously. This saves a significant amount of time, especially the time spent for switching between beams. The most important aspect here is that the coverage of the wide area is simultaneous.

IV. MIMO RADAR

MIMO stands for Multiple-Input-Multiple-Output, a technology that is coming up in communications in order to improve the coverage, data rate and/or signal quality. For the future radar the same improvements are needed. MIMO radars simultaneously radiate uncorrelated signals, for instance, in different directions, or in the same direction with orthogonal polarization [4]–[7]. This improves the coverage and the received information quality. An example for the radiation of three simultaneous beams with a MIMO radar is shown in Fig. 6. The decorrelation between the transmitted signals is realized by OFDM spectral-interleaving [8]. In this case the total bandwidth for each transmit-receive channel is retained hence there is no degradation in the radar range resolution.

![MIMO transmit array with three beams in the same direction.](image)

Fig. 6. MIMO transmit array with three beams in the same direction.

The decorrelation of each transmit signal is important, otherwise small, remote targets might not show up on the radar image. In practice a decorrelation of more than 70 dB can be realized with OFDM interleaved signals.

For near-range radars e.g. automotive radars, the coupling transmit-receive should be less than -40 dB, because these radars usually transmit while they receive the near range signals.

V. ARRAY IMAGING

While the knowledge and the significance of DBF and MIMO radar are already widespread, the radar community is less aware of array imaging. This technique combines the features of DBF with MIMO radar. The basic idea of array imaging is very simple: multiple transmit antennas radiate their uncorrelated signals in the same area, the reflected multiple signals are then received by each of the receive array antennas. For far-field operations the phase difference is assumed to be only due to the different positions of the transmit antennas since the distance from the far-field target to each antenna element is much larger than the antenna element spacing. This offsets the effect of the antenna elements’ real position relative to the object. Fig. 7a shows the real antennas and the radiation towards a far-field target. The received signals for the two radiations have a phase difference, marked by the two corresponding phase fronts. The phase front of Tx1 is delayed due to its offset compared to Tx2. The lower phase front would also result if two additional receive antennas are placed further left (Fig. 7b). They appear as ‘virtual receive antennas’ and their receive signals can be processed like real signals. The receive antennas are imaged at the transmit antenna and form a larger virtual array, at no additional cost or space.

In order to avoid redundant multiple copies of the same received signal with the same phase difference, the spacing \(d_{Rx}\) of the receive antennas and \(d_{Tx}\) of the transmit antennas are arranged in such a way in equation (6) to lead to the widest antenna basis.

\[
d_{Tx} = N_{Rx}d_{Rx} 
\]  

(6)

The transmit antennas in this case usually have a spacing of more than a wave length. This results in grating lobes at the transmit array radiation pattern. By spacing them according to equation (6), the nulls of the receive array will coincide with the transmit grating lobes to eliminate them, see Fig. 8 for a 3Tx by 3Rx array example.

![Array imaging with a MIMO radar for a simple 2Tx by 2Rx system; a) phase fronts for the two Tx-Rx arrays; b) imaging the phase front on the virtual Rx antennas.](image)

Fig. 7. Array imaging with a MIMO radar for a simple 2Tx by 2Rx system; a) phase fronts for the two Tx-Rx arrays; b) imaging the phase front on the virtual Rx antennas.
Fig. 8. Array factors for array imaging with a 3Tx by 3Rx array.

VI. RADAR 2020 SYSTEM BLOCK DIAGRAM

The integration of a MIMO radar with DBF operated with OFDM signals is shown in Fig. 9. The Radar 2020 system is completely digital except for the frontends. These frontends are identical at the transmit and receive side respectively for each channel. For higher frequencies and shorter ranges, e.g. in automotive applications, they may be completely integrated in MMICs. OFDM MIMO signal generators are already available on the market for certain applications. The OFDM parameters can then be set according to the application requirements.

VII. RADAR SIGNAL PROCESSING

The processing strategy for future radar systems in this paper is limited to OFDM. The transmit signal is given by equation (2). The receive signal $y(t)$ varies in complex amplitude $A$, range $R$ and Doppler $f_D$, see equation (7).

$$y(t) = A \sum_{m=0}^{M_{sym}-1} \sum_{n=0}^{N_{C}-1} D_{Tx}(mN_{C}+n) \exp \left( j 2\pi n \Delta f \left( t - \frac{2R}{c_0} \right) \right) \cdot \exp \left( j 2\pi f_D t \right) \text{rect} \left( t - mT_0 \right).$$

(7)

For the evaluation of the reflected signals the information content in the OFDM receive signal is discarded via an element-wise division of the received signal by the known transmit signal. What is left then are the amplitude, time shift (range) and frequency shift (Doppler). The resulting equation (8) in the frequency domain has a linear dependency with $n$ and $m$, which corresponds to the subcarrier index in the frequency axis and the symbol index in time axis respectively.

$$Y(m,n) = A \sum_{n=0}^{N_{C}-1} \exp \left( -j 2\pi n \Delta f \frac{2R}{c_0} \right) \sum_{m=0}^{M_{sym}-1} \exp \left( j 2\pi f_D mT_0 \right)$$

(8)

From the extracts of equation (8) the range and Doppler can be determined by simple Fourier transformations (IFFT, FFT). In summary the angular, range and Doppler processing are all just Fourier transformations. Simulations and experiments have proved that an arbitrary number of targets can be resolved using this technique [9], limited only by the physical constraints such as the bandwidth $B$ and receive power $P_{Rx}$. The compression gain is the product of $M \times N$. Super resolution algorithms like MUSIC can also be applied to generate an enhanced angular pseudo-spectrum. The overall efficiency of the Radar 2020 will in practice be around 6 dB to 10 dB higher than for the current radars; and this can be invested in wider beams for simultaneous coverage of areas of interest, for example for airport radars.

VIII. RadCom

The coding of the radar signal with OFDM or similar communication codes offers the possibility to include information in the radar signal. With one transmission and one hardware equipment the systems can operate as radar and communication devices simultaneously. Applications can be the communication of automotive radars with other cars or infrastructure or military battlefield radars, see [10]–[13].

IX. CONCLUSION

The new system technologies of the Radar 2020 will allow complete new functions and applications, which can replace most of the existing system concepts [14]. The radars of the future will render more information, be more flexible and will also be smaller and significantly cheaper. Best of all most of these technologies for the future radar systems are already available from other applications; they just have to
be just integrated in the future radars. The Radar 2020 will revolutionize radar system engineering, and foreseeably, also the radar market.

REFERENCES