miniCODIR – An Agile Radar Network for Experimental Research on Advanced Sensing Techniques

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ABSTRACT

We present the fully adaptive radar network "miniCODIR" as a flexible system for radar research in different fields such as distributed sensing, multistatic sensors, UAV detection and classification, cognitive radar and joint radar and communication. The miniCODIR system has been developed as part of the work for the NATO RTG SET-227 "Cognitive Radar" and has since been deployed for a trial with the RTG SET-307 "Advanced radar techniques for robust situation awareness and threat assessment considering Class I UAS in complex environments". An application in the RTG SET-302 "Cognitive Radar" is planned.

The first part of the paper is dedicated to the presentation of the capabilities of the system. The miniCODIR system consists of four, real-time adaptable X-band radar nodes with a centralized control, processing and tracking unit. Each radar node features a transmit chain with up to 80 MHz instantaneous bandwidth and a 2-channel receive chain with a digital correlation and decimation step. Each node can be configured either as a monostatic radar or as a bistatic receiver listening to the echoes from one of the other nodes. The centralized processing unit consists of a signal processor with CFAR detection for each radar node, a multi sensor tracker to fuse the detections, a fully adaptive waveform optimizer and a common display and control GUI.

In the second part, experimental results from recent research campaigns are discussed. The first application focuses on UAV detection and tracking in an urban environment with a distributed sensor setup to monitor selected low flight axes. In a second example, we present the UAV detection and classification with a ubiquitous radar with a monostatic or bistatic sensor setup. The third example presents the fully adaptive optimization of radar parameters to minimize radar resources such as bandwidth or transmit time. Finally, we present the extension of the miniCODIR hardware with DAB modulation- and demodulation components to demonstrate the joint radar and communication operation.

1.0 INTRODUCTION

Recent advantages in radio frequency (RF) technologies such as software defined radios (SDR), arbitrary wave generation (AWG) or fully digital arrays are enablers for new sensing concepts such as radar networks, cognitive radar (CR) or joint radar and communication (JRC). Such developments often start with the proposal of theoretical concepts and algorithms, followed by a validation through simulation. However, the subsequent experimental verification is often a big challenge because suitable a radar system are not available.

The miniCODIR system has been developed to help partially bridge this gap between proposed algorithms and experimental verification. Originally, the system was built as a test environment for cognitive radar experiments. Thanks to the flexibility of the SDR-based modules used for signal generation and processing, it was possible to adapt the system to other purposes as well.

This paper is structured as follows: After the introduction, the design and capabilities of the miniCODIR system and its hardware and software components are described. Then, several application cases of recent campaigns are presented to explain the testbed capabilities with practical examples. Finally, we conclude the paper with a summary and an outlook.

2.0 DESIGN AND CAPABILITIES

The miniCODIR testbed consists of four, real-time adaptable X-band radar sensors linked to a centralized control, processing and tracking unit (CP). Each sensor uses the waveform parameters defined by the CP for monostatic radar operation and sends the digitized baseband signal return to the central processor for further signal processing. The CP controls the radar operation parameters of each sensor and implements the radar processing chain. The sensors are connected to the central computer via a Gigabit Ethernet connection, to transfer raw sensor data to the central processor and to send control statements to the sensors. This interface uses the `libiio-` library from Analog Devices [1] and has been implemented in Matlab and C++.

2.1 Sensor

Each sensor consists of a backend and a RF-frontend. The frontend includes a coherent, double super heterodyne mixer board for up- and down-conversion of transmit and receive signals, a common local oscillator (LO) and clock generation board, a power amplifier board on the transmit path and low noise amplifier (LNA) boards close to the two receive antennae. The LO frequency for the second mixing stage defines the centre frequency of the transmit signal and is software adjustable by the central processor. The backend consists of an Ethernet I/O interface, a GPS receiver for time stamping, the A/D and D/A conversion modules and a Xilinx Zynq 7030 System on chip (SoC). The latter generates the transmit waveform and the pre-processes the digitized data stream from the receive channels.

The signal generation and pre-processing depends on the waveform type. For linear frequency modulated (LFM) waveforms, the baseband signal is generated by a DDS chip integrated the FPGA of the SoC. Such a waveform is defined by the start and stop frequency and the pulse duration. On the receive side, the A/D converted chirp r_n is digitally dechirped by multiplying r_n with a complex conjugate copy of the transmit chirp s_n. The dechirped signal $y_n = s_n^* r_n$ is decimated, filtered and transferred as an IQ data stream to the central computer for further processing. If the AWG waveform mode is used, the waveform needs to be defined as a list a complex of values before being transferred to the FPGA memory. In operation, the stored waveform is sent repetitively out to the transmit chain. On the receiver side, the received signal r_n is correlated with the transmit signal s_n using a Fourier transform based correlation. The correlation product in frequency space $\hat{y}_n = \hat{s}_n^* \hat{r}_n$ is decimated and streamed to the central computer for further processing. Here, the hat accent represents the Fourier transform of the signal.

A simplified sensor block diagram is shown in Figure 1 and a photo of the sensor is provided in Figure 2. Typically used parameter ranges are summarized in Table 1

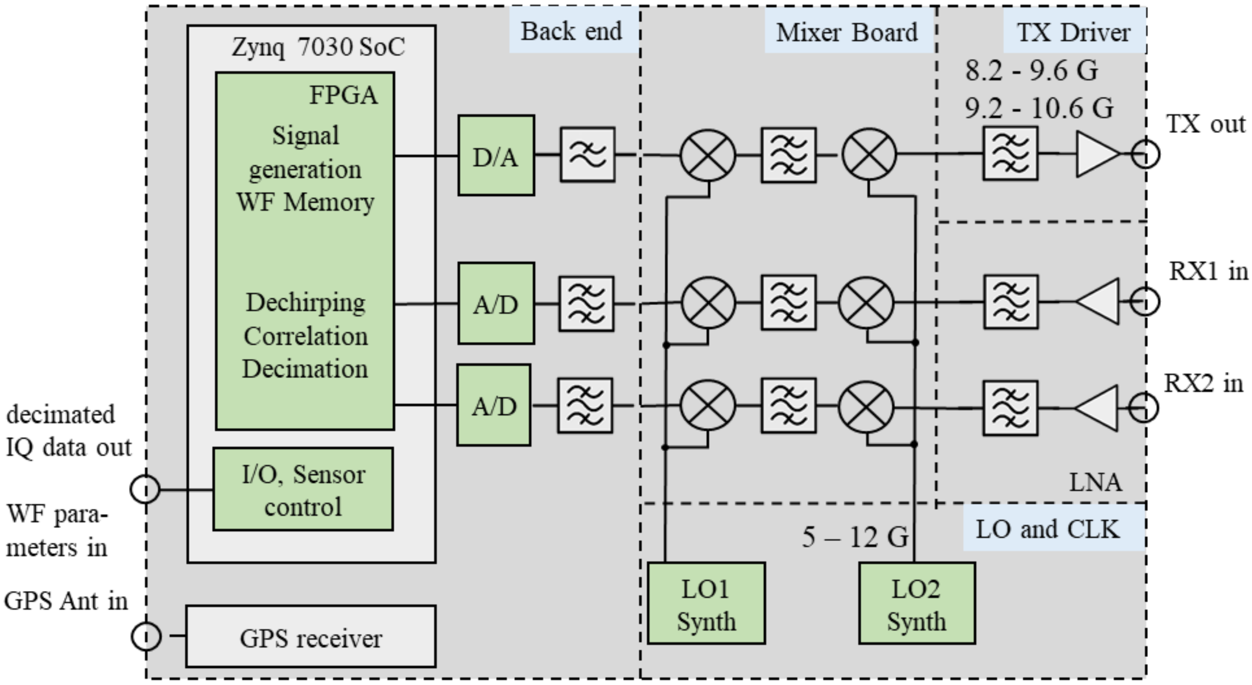


Figure 1: Simplified block diagram of one of the miniCODIR sensor nodes.

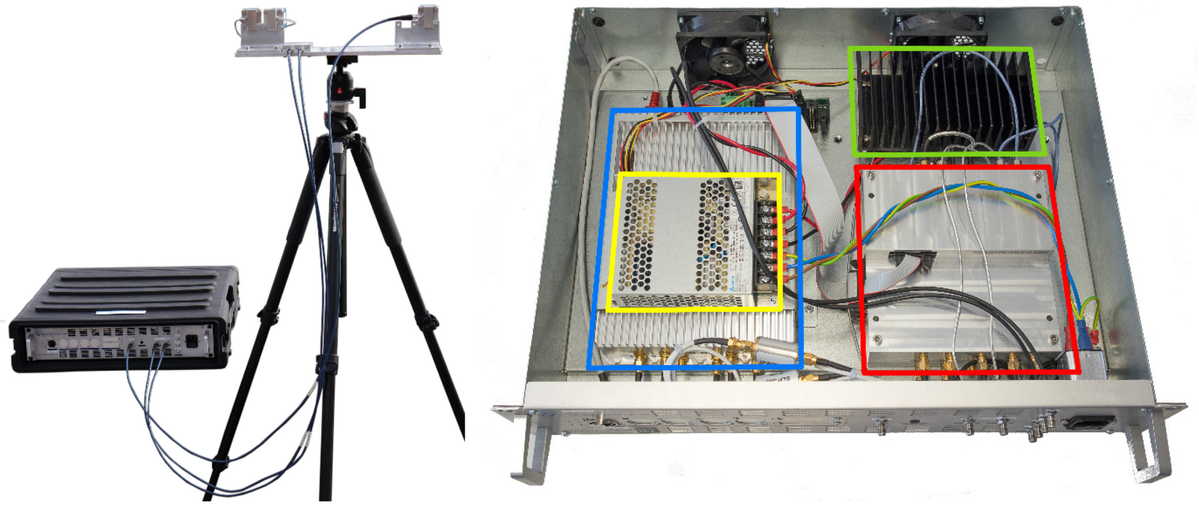


Figure 2: The miniCODIR testbed. A picture of the deployed sensor node with antennae and sensor rack is shown on the left. The view into the sensor rack (right panel) shows the backend (blue box) and the power supply (yellow box) on the left side of the rack while on the right half, the frontend modules (red box) and the power amplifier (green box) are visible.

Table 1: Typical miniCODIR operation parameter ranges used during experiments and tests.

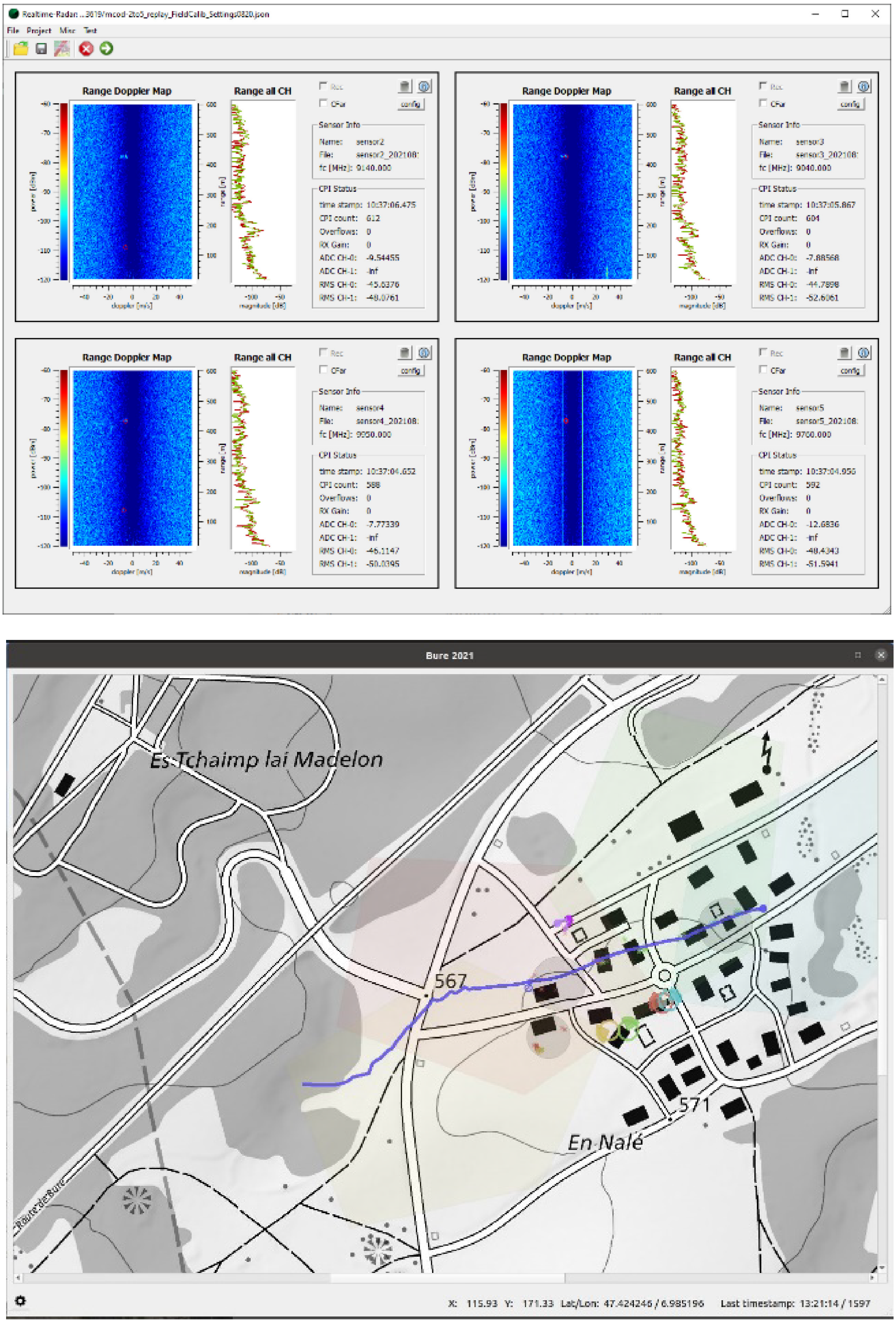
Parameter	Value
Centre frequency	8.2 GHz – 10.6 GHz
Instantaneous bandwidth	Adjustable, typically 20 MHz - 80 MHz
Transmit Power	Adaptive, up to 33 dBm
Waveform Type	LFM (DDS generated) or AWG (stored in the memory)
Pulse repetition frequency	Adaptive, typically 1.7 kHz – 13.6 kHz
Processed pulse length	Typically 80%-90% of the pulse repetition interval
Number of transmit (receive) channels per node	1 (2)

2.2 Central Processor

The central processor (CP) contains the software modules to process the incoming IQ data from the sensors (sensor processor), to track the targets (sensor tracker) and to control the sensors (controller and operator GUI). These modules run in parallel as separate threads. Each signal processor is assigned to one of the sensors and takes the decimated IQ data from the corresponding sensor as input for range-Doppler processing. The comparison of phase and amplitude values between the two RX channels provides a direction of arrival (DOA) estimation. A CFAR detector finally extracts a list of measurements (detections) and sends them to the controller as input for multisensor tracking in the Cartesian plane using a centralized extended information filter (EIF) [4] tracker. This formulation is algebraically equivalent to the more common extended Kalman filter (EKF) tracker but has the advantage, that the track information update can be written using the information matrix (inverse covariance matrix).

Currently, a C++/Qt and a Matlab implementation of the CP is available. The C++/Qt implementation processes and records all sensor data in real-time and presents the data on two displays. Technical data, such as radar settings, range profiles and range-Doppler maps are displayed on the maintainer screen while sensor products such as plots and tracks are displayed on the operator screen (see Figure 3). This implementation is primarily used for operative demonstrations of distributed sensing and for IQ data recording but is not able to real-time adapt the sensor and processing parameters for cognitive radar operation.

On the other hand, the Matlab version implements an additional controller module with decides on the optimal waveform or set of radar parameters for the next track update (see Sect. 2.3 for details). It does not process all coherent process intervals (CPIs) and does no record the IQ data. The modules run in separate Matlab instances with a shared memory space for cross-module data exchange and coordination (Figure 4).



Sensor Info
Name: sensor2
File: sensor2_202108:
fc [MHz]: 9140.000

CPI Status
time stamp: 10:37:06.475
CPI count: 612
Overflows: 0
RX Gain: 0
ADC CH-0: -9.54455
ADC CH-1: -inf
RMS CH-0: -45.6376
RMS CH-1: -48.0761

Sensor Info
Name: sensor3
File: sensor3_202108:
fc [MHz]: 9040.000

CPI Status
time stamp: 10:37:05.867
CPI count: 604
Overflows: 0
RX Gain: 0
ADC CH-0: -7.88568
ADC CH-1: -inf
RMS CH-0: -44.7898
RMS CH-1: -52.6061

Sensor Info
Name: sensor4
File: sensor4_202108:
fc [MHz]: 9950.000

CPI Status
time stamp: 10:37:04.652
CPI count: 588
Overflows: 0
RX Gain: 0
ADC CH-0: -7.77339
ADC CH-1: -inf
RMS CH-0: -46.1147
RMS CH-1: -50.0395

Sensor Info
Name: sensor5
File: sensor5_202108:
fc [MHz]: 9700.000

CPI Status
time stamp: 10:37:04.956
CPI count: 592
Overflows: 0
RX Gain: 0
ADC CH-0: -12.6836
ADC CH-1: -inf
RMS CH-0: -48.4343
RMS CH-1: -51.5941

X: 115.93 Y: 171.33 Lat/Lon: 47.424246 / 6.985196 Last timestamp: 13:21:14 / 1597

Figure 3: Screenshots from the C++/Qt implementation of the central processor. Upper panel: Maintainer display to configure and monitor the sensor nodes. Lower panel: Depiction of plots and tracks on a map.

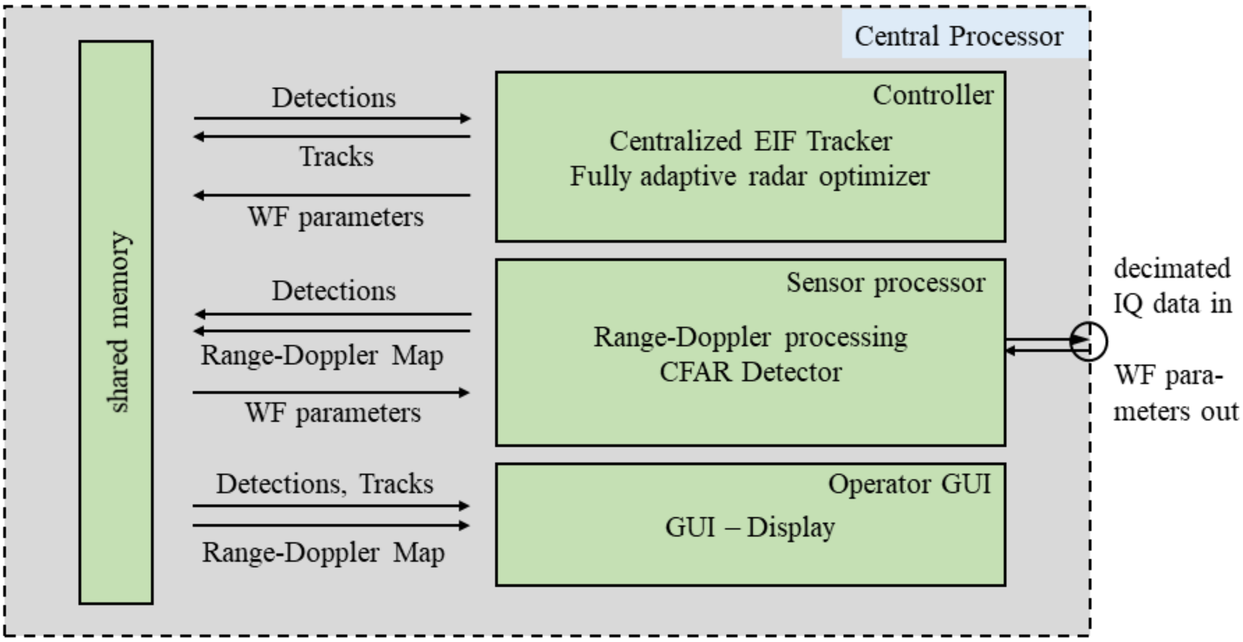


Figure 4: MiniCODIR central processor functional block diagram for the Matlab implementation. For simplicity, only one sensor processor is shown. The arrows indicate the data products transferred between the different processing modules.

2.3 Cognitive Radar Operation

For cognitive radar experiments the Matlab implementation of the CP (see Sect. 2.2) is used. An additional controller module which decides on the optimal waveform or set of radar parameters has been integrated in the processing chain of the CP to form a perception action cycle (PAC). The use of a PAC is considered as precursor to a cognitive radar. A corresponding block diagram is presented in Figure 5. The controller module implements the fully adaptive radar (FAR) framework for target tracking [3] and adapts it to track multiple targets in a multi-sensor environment. The FAR optimization adapts the radar parameters θ_n at each track update x_n based on the a priori state information and the radar parameter dependant measurement covariance matrix. The controller decides on the sensor parameters for the next measurement by minimizing a scalar cost function that balances the cost to assure a good tracking performance with the cost for the sensors to do the measurement. To determine the optimal radar parameter set with minimal cost, the controller evaluates the predicted track accuracy cost for each potential parameter set using the predicted posterior information matrix. On the other hand, the sensor cost depends on the optimization goal. More details are given in [2].

If the controller decides to change the radar parameters or waveform for the next track update, the new information is written to the share memory (see Figure 4). At the next CPI, the sensor processors pass this information to sensor backend, which updates the waveform immediately ready for the next pulse transmission. The change of WF parameter (in the LFM mode) or the transfer of a new waveform to the FPGA memory (in the AWG mode) takes a few milliseconds. The complete waveform change process including waveform computation, transmission, reception and processing of the data with the new parameters takes roughly 300~ms, which is enough for a FAR adaptation at a rate commensurate with the track update interval. Within the current architecture, a code optimization for a CPI-to-CPI adaptation is achievable.

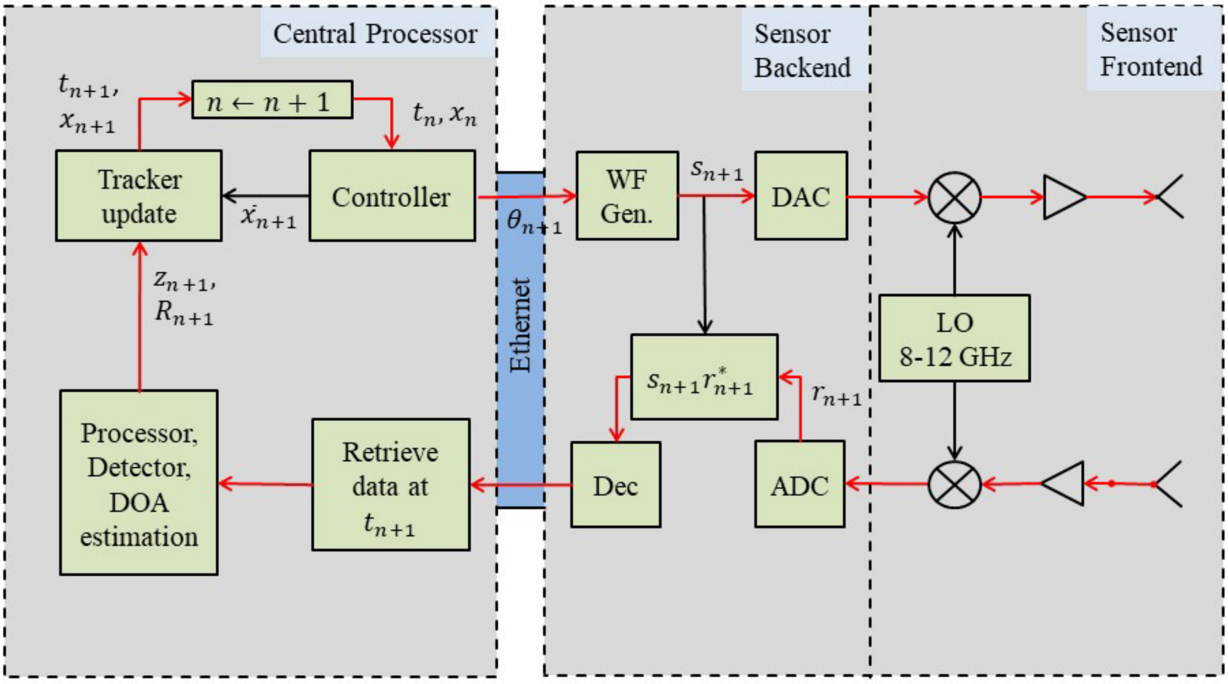


Figure 5: A simplified block diagram describing the cognitive radar operation. The Perception Action Cycle is highlighted in red. For simplicity, only one sensor is shown.

2.4 Bistatic Radar Operation

Each miniCODIR node is a monostatic radar sensor. However, a sensor node can also be setup as a bistatic receiver by listening to the target echoes from another miniCODIR node transmitting on the same centre frequency band as the bistatic receiver. The bistatic node generates the same transmit waveform as the transmitting node. However, it does not transmit it, but only uses the waveform to dechirp the received target reflections. The processing steps done by the CP are formally identical to the monostatic case, with the difference, that the bistatic range instead of the monostatic range is estimated. On the tracking side, the bistatic geometry needs to be taken in to account in the measurement matrix and the coordinate conversion between the sensor centric system and the Cartesian system of the tracker.

A critical component of a bistatic operation is an exact time synchronisation between the signal generators of the transmitting and the bistatic receiver node. For this purpose, the miniCODIR nodes are synchronized to GPS time. Each sensor implements a feedback loop that adjusts the control voltage of the reference OCXO oscillator in order to minimize the phase error between the external GPS PPS and an internal PPS, which is generated by a counter running on a 250MHz clock derived from the reference OCXO (see Figure 6). For more details, see [5].

3.0 APPLICATION CASES

3.1 Distributed Sensing and Tracking in an Urban Environment

The first application considers a C-UAV scenario in an urban area with limit sensor coverage due to building obscuration. The miniCODIR radar network is tasked to detect and track an UAV attacking a target building (see Figure 7) at low altitude, in the shadow of nearby buildings. Such a scenario cannot be covered by a single scanning surveillance sensor. The sensor nodes are setup to monitor the direct vicinity of the target building (red sensor node) but also to observe the incoming streets (blue, magenta node) to the area. For a fictious attack from the west to the target building, the target is first detected by the blue sensor node, followed by the magenta, the yellow and the red sensor node. The multisensor tracker is able to track the target continuously, handing the target over from one sensor to the next (Figure 8).

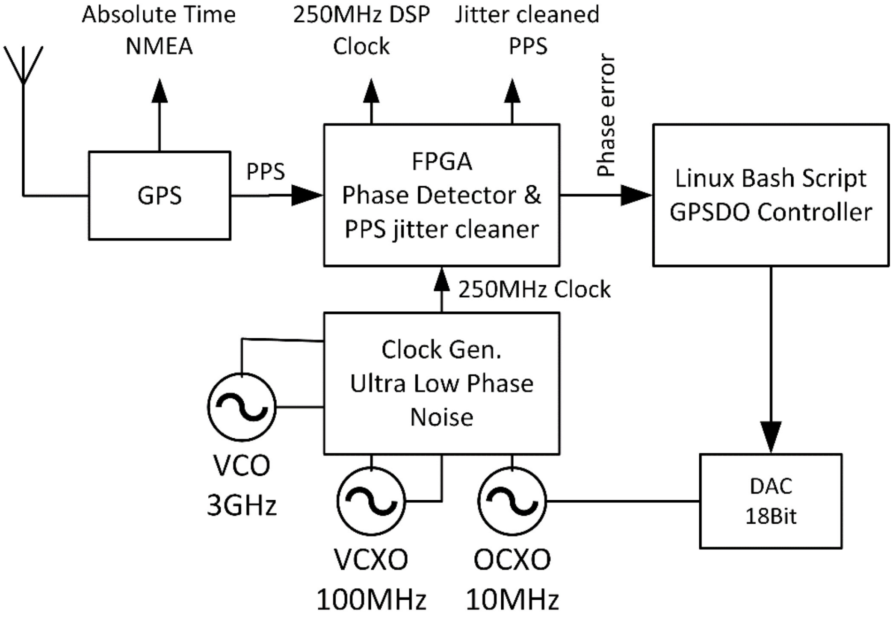


Figure 6: Time synchronisation with an external GPS source. Shown is the feedback loop to control the OCXO reference oscillator.

Figure 7: A fictious UAV attack from the west to the target building (red sensor). The target enters the scene from the west and is first detected by the blue sensor node, followed by the magenta, the yellow and the red sensor node (coloured dots). The sensor positions and their field of view are shown by coloured sectors

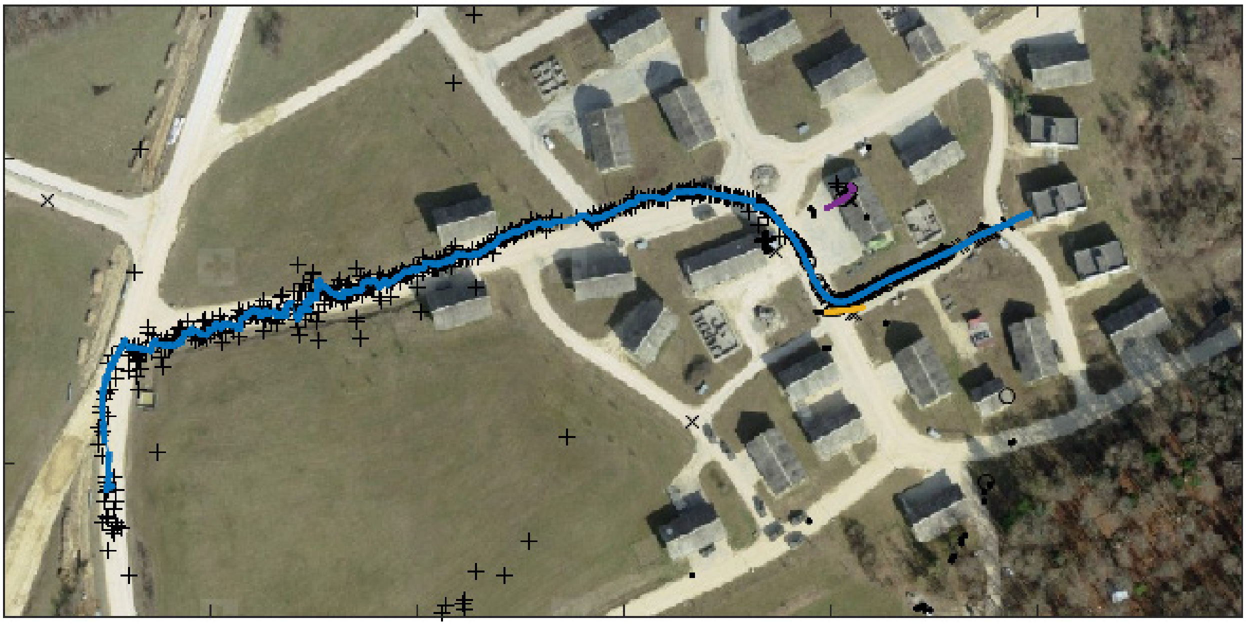


Figure 8: The UAV path to the target building is tracked continuously and is handed over from one sensor to the next. The track updates are shown as coloured dots, the sensor detection are depicted as black symbols.

3.2 Bistatic Drone Detection

The second application uses data recorded during the NORSWARM campaign conducted by the NATO RTG SET-307 in summer 2022. A first miniCODIR node (“node 1”) is setup as a monostatic radar to illuminate a group of four drones flying towards the radar in a circling pattern. A second miniCODIR node is setup as bistatic receiver (“node 2”) using the transmitter of node 1 as illuminator to observe the drones with an offset angle of about 45°. Finally, to assess the bistatic radar performance, a third radar node (“node 3”) at the position of the bistatic receiver but operating as a monostatic radar on a different carrier frequency has been setup up. Figure 9 shows, that the detection performance with the bistatic receiver is very comparable to the detections with the two monostatic radars because all sensor nodes use the same RF components. Limitations in coverage or accuracy are primarily due to the type of antenna used. For example, node 2 uses 20 dBi TX and RX horns with a narrow field of view (FoV) aligned to the approaching drone while node 5 uses 10 dBi horns with an extended FoV but with limited gain compared to node 2. The range jitter with the bistatic node is larger than the range jitter with the monostatic sensors, but is still negligible compared to the position jitter due to the DoA estimation.

3.3 Cognitive Radar with a Perception Action Cycle

The following example demonstrates to real-time adaptation of the sensors using a perception action cycle. The scenario includes a single moving target and two sensor nodes. One node has a full coverage of the target path while the second node has only a partial view. In this example, the sensors use fixed sensor parameter but at each track update, the sensor network has the option either to illuminate the target with both sensors, with sensor 1, with sensor 2, or not to illuminate at all. The goal of the optimizer is to use minimal sensor illumination effort (minimal emission time) for the given task (detect and track of a single target). The normalized sensor cost for this goal is chosen as 0 (no illumination), 0.5 (illumination with one node) and 1 (illumination with both nodes) while the track accuracy cost is given by the sum of the diagonal elements of the predicted posterior information matrix.

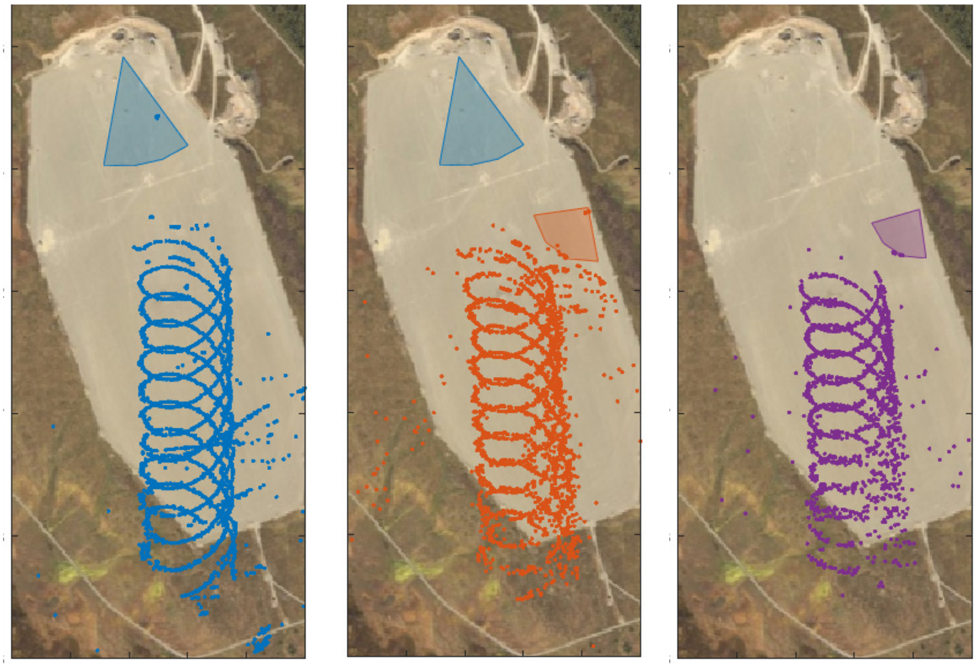


Figure 9: A group of UAVs detected by three different miniCODIR sensor configurations. The dots show the target detections while the triangles indicate the sensor position and the corresponding field of view. Node 2 (middle panel, red) is a bistatic receiver with the transmitter of the monostatic sensor node 1 (left panel, blue) as illuminator. Node 3 (right panel, magenta) is a monostatic node with an extended FoV. The target position distortion visible primarily in the middle and right panel is due to the slant range error.

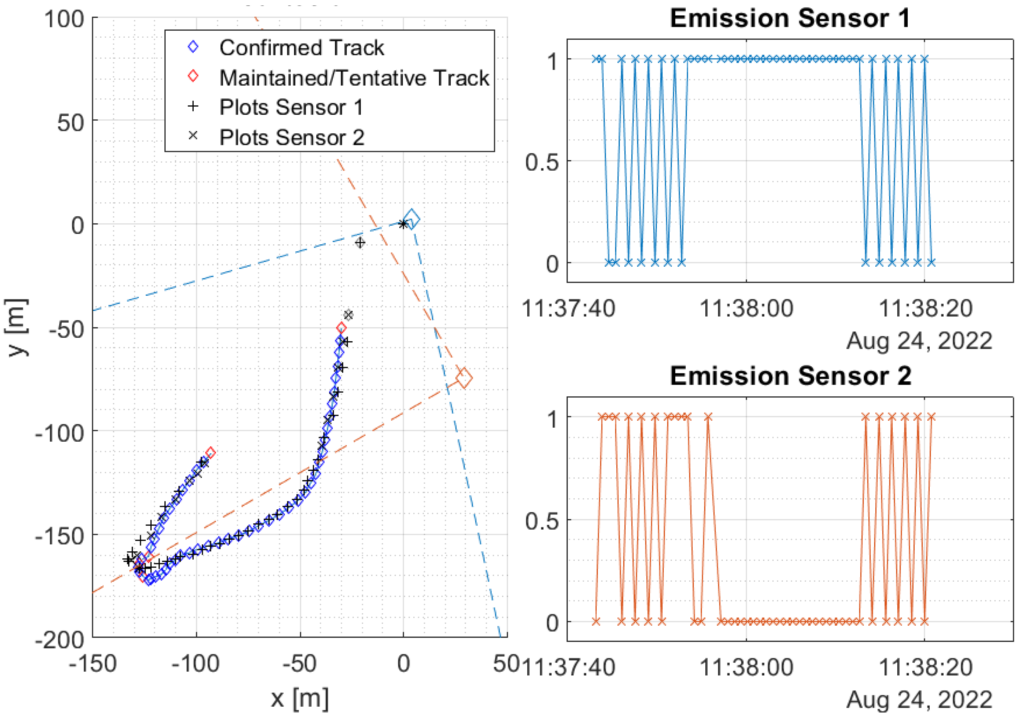


Figure 10: Cognitive radar adaptation of the sensor usage in a network with two nodes. Left panel: Tracked target (blue) and FoV of the sensors. Right panel: Sensor usage (1: sensor is transmitting, 0: no transmission).

Figure 10 shows the target track with the FoV of the two nodes and the controller's decisions for the two nodes. If the target is in the FoV of both sensors, the controller decided to illuminate the target alternately by sensor 1 and 2. Compared to a simultaneous illumination with both sensors, this decision of the controller consumes less sensor resources with only a small degradation in track accuracy. A very similar result is reported in [2]. If the target is out of the FoV of a sensor, its transmitter is switched off to save sensor resources (see Figure 10, middle part of the track).

3.4 Joint Radar and Communication

Recently, the miniCODIR hardware has been adapted to demonstrate joint radar and communication (JRC) operation using Digital Audio Broadcasting (DAB) waveforms. The original waveform has been slightly adapted for radar operation by scaling up the sampling rate by a factor of 7.6294. This leads to a signal bandwidth of 11.72 MHz (original DAB: 1.5376 MHz), a PRI of 164 us (original DAB symbol length: 1.246 ms) a range resolution of 12.8 m and a maximal unambiguous velocity of ~50 m/s. Apart of this modification the standard DAB modulation and demodulation methods are used.

The JRC operation has been demonstrated with a setup of two miniCODIR nodes. A corresponding block diagram is shown in Figure 11. The communication functionality was implemented with a DAB modulator to generate the transmit signal at the first node and a DAB demodulator at the receiver of the second node to recover the transmitted data. By comparing the demodulated signal with the original data before modulation, the bit error rate (BER) can be determined. The radar functionality is implemented similarly to a passive radar by correlating the received target returns with a regenerated version of the direct signal at the second node. The regeneration (demodulation and re-modulation) removes the noise from the direct signal and ensures a cleaned direct signal as a reference for correlation.

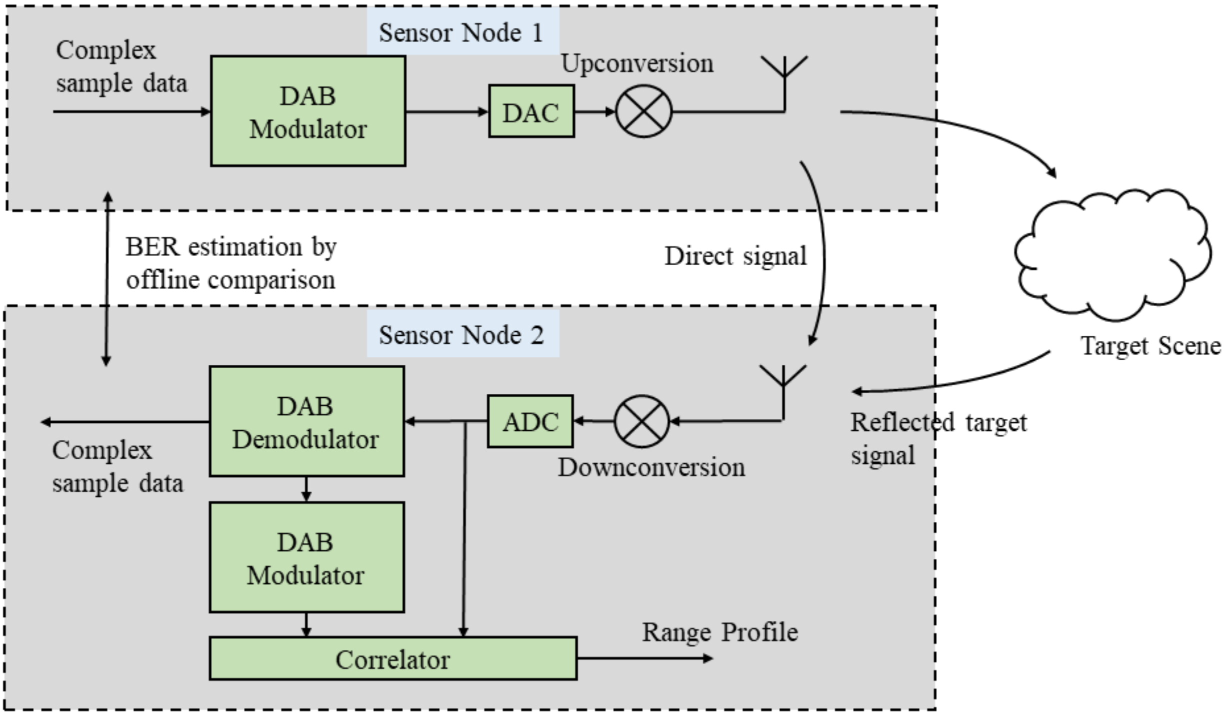


Figure 11: A demonstrator setup for joint radar and communication using DAB waveforms.

4.0 CONCLUSION

In this paper we have present the fully adaptive radar network "miniCODIR" as a small, flexible system for radar research in different fields such as distributed sensing, UAV detection and classification, cognitive radar and joint radar and communication. The hardware components, such the signal generation and the frontend electronics, the data pre-processing in the FPGA, and the radar processing chain components such as detector and multisensor tracker have been explained in detail. The testbed capabilities have then been illustrated by four practical application cases from different research fields of advanced sensing techniques.

The first example demonstrates the fusion of sensor information in a distributed sensing setup for UAV detection and tracking. In the second example, the above case has been generalized by considering a bistatic setup consisting of a bistatic receiver node and a another miniCODIR node that is transmitting at the same centre frequency. In a third example, we illustrate a fully adaptive radar network that adapts its transmission parameters (waveforms) in real-time to minimize the total sensor usage (illumination time) while assure a predefined tracking accuracy. Finally, the joint radar and communication (JRC) operation has been demonstrated in a fourth example where a DAB signal was exchanged between two nodes (communication) while simultaneously determining the distance to a nearby target (radar).

Although developed for cognitive radar experiments, the sensor network has been adapted to other experimental applications such as bistatic operation of JRC. This flexibility was enabled on the one hand by the software-programmable Zync 7030 SoC for flexible signal generation and processing and, on the other hand, by the `libiio-` library, which enabled the development of a data and control interface to the sensor backend using high-level languages.

5.0 REFERENCES

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