Joint Waveform Design for Multifunction Radio Frequency Systems

1. Main objective and summary of the project.

Multi-Function Radio Frequency (MFRF) systems aim to integrate several Radio Frequency (RF) functions, such as radar, communication, Electronic Warfare (EW) and navigation, on a shared set of electronics and antenna to be more flexible and increase overall performance. With flexible software and hardware, the system could change its role dynamically based on the task it is trying to solve. In addition, a decrease in Size, Weight And Power (SWAP), reduction in integration and training time, cost reduction and easier handling of electromagnetic interference and compatibility are potential benefits for MFRF systems [1, 2].

As stated in [3], the challenge of a MFRF system is to meet the required performance but with the energy and time budget available to undertake other roles. One approach to overcome this is to combine several RF functions on a single joint waveform. Information could be embedded in the radar waveform and vice versa, but this also comes at a cost. Several studies have shown how radar and communication systems could operate on the same waveform, and in recent years they also include EW. These studies are based on one basis RF functionality (e.g. only radar or communication) whit some extra functionality added to the waveform. In this PhD project we want to embrace multifunctionality from the start rather than considering it as a primary RF function whit added extra functionality.

The PhD project will explore how a joint waveform can combine several RF functions on a single transmitted signal by defining what makes a good radar, communication, EW and navigation waveform. Based on this knowledge, several types of waveforms modulators will be analyzed to determine their combined joint RF functionality and flexibility. The increased flexibility could potentially increase the overall performance of distributed RF systems. Therefore, this project will explore how distributed MFRF systems compare to other more traditional RF systems. Based on these findings, a concrete application will be developed and tested. Both simulation and real-world experiments will be conducted to verify MFRF systems flexibility and capability.

2. Project background and scientific basis.

Recent technological advances in direct RF digitization, increased processing power and broadband RF components enable several RF functions to be integrated on a MFRF system. State-of-the art RF System-on-Chip (RFSoC) integrated circuit architecture now combines high-accuracy digital and analog converters, operating at Giga Samples Per Second (GSPS), with programmable heterogeneous compute engines. Xilinx Zynq Ultrascale+ RFSoC Gen 3 can now digitalize RF signals up to 6 GHz analog input frequency in 8 channels at 5 GSPS each in parallel [4]. Combined with powerful programmable logic in form of Field Programmable Gate Array (FPGA), application and real-time processing units (ARM processors), high speed embedded and external memory and high-speed connectivity, several RF functions can now be integrated on a single chip.

MFRF systems originate from the development of Active Electronically Scanned Array (AESA) antenna technology, which made it possible to perform a large number of RF functions from a common, low signature aperture [5]. In its early stage this made it possible to develop Multi-Function Radars (MFR) which integrate multiple radar functions, such as track-while-scan, into one single system [3]. Modern broadband AESA architectures are reconfigurable and gives the opportunity to form simultaneous transmit and/or receive beams in independent directions with different beam patterns and waveforms, hence enabling MFRF systems to combine radar, communication and EW (Electronic Support (ES) and Electronic Attack (EA)). A conceptual diagram form [1] is often used to describe a general MFRF system, shown in Figure 1.

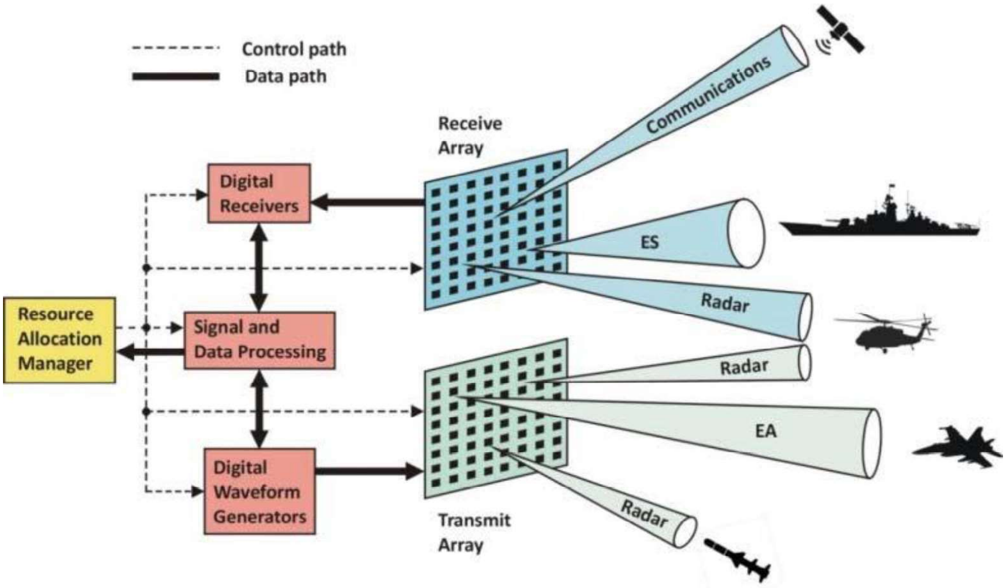

Figure 1: Conceptual diagram for MFRF system [1]

In Figure 1, a digital processing chain close to the antennas is used to digitalize and compute different RF waveforms, and a resource allocation manager is used to orchestrate and control the different RF functions. In [3] it is stated that the key to MFR operation is the management of time and energy budget, often called Radar Resource Management (RRM). RRM is a large research field, whit a large number of publications [6-8], but according to [3] there seems to be a lack of open literature regarding general resource allocation managers capable of managing other RF functions in addition to radar.

Despite the lack of studies on general resource allocation managers, there are several studies on how different RF functions can operate together [9-12]. Chiriyath *et al.* described in [13] how radar and communication can be combined either via co-existence, cooperation or co-design. Co-existence means that the RF functions are uncoordinated and share no information and treat each other as interferers. Cooperative means that separate RF functions share some information to mitigate interference and mutually optimize their performance. In [14] the authors showed how cooperative radar AESA system and EW system could minimize the radar interference by using information to predict the EW system's behavior and compromise the radar waveform. Cooperative systems also have their challenges, both [3] and [15] point out the difficulty of a communication protocol to seamlessly integrate to radar operation. Co-design means that the system is designed from the ground up to maximize their joint performance. This means that they operate in a coordinated manner and share technologies such as antenna, waveform, amplifiers etc., as shown in Figure 1.

In co-designed MFRF systems the digital waveform generator can either generate RF waveforms separately or jointly. In separate waveform generation each RF function is individually generated and separated in either time, frequency, code, antenna or a combination of these. Figure 1 is an example of separate digital waveform generation where each RF function is separated by the AESA antenna. When several RF waveforms operate in parallel they may interfere with each other. Therefore, an idea is to combine several RF functions on a single joint waveform to mitigate the interference problem.

Several studies have looked into the possibility of combining radar and communication on a joint waveform. It was already described back in 1963 by [16], but the data rate achieved then was low. Whit increased processing power the idea has regained its interest in recent years. Barrenechea *et al.* showed [17] how information could be encoded onto a Frequency Modulated Continuous Wave (FMCW) radar. Both [18] and [19] showed that Orthogonal Frequency Division Multiplexing (OFDM) and Direct Sequence Spread Spectrum (DSSS) have suitable properties as a joint waveform, and Sanson *et al.* [20] showed how Filter Bank Multicarrier (FBMC) can be used to improve spectral efficiency and radar performance. OFDM has also been used in recent studies to combine radar, communication and EW in form of jamming (EA) [21, 22].

In [12] the authors introduced the concept of collaboration in addition to co-existence, cooperation and co-design. Collaboration means that units geographically separated do not regard each other as interferers but exploit their joint knowledge and geographical separation to promote overall performance. There are several studies that show how distributed RF systems can increase performance when sharing information and collaborating. In [23] the authors showed how a distributed radar sensor network increased detection performance of fluctuating targets compared to a standalone system by sharing and comparing target information. The authors of [24] studied how distributed phased array radars can improve reaction time against threats when using a coordinated RRM compared to an independent RRM, at the expense of sharing data across a communication channel.

Collaborating across RF functions could also increase overall system performance. As described in [15] modern communication systems need to perceive the environment to optimize performance and throughput. Both radar, ES and positioning via navigation systems could give situational awareness to communication systems, hence enhancing system performance. This is one of the reasons why the authors of [25] promotes a co-designed waveform that combines communication and radar sensing for beyond 5G and 6G communication systems. EW could also benefit from using and collaborating with other RF functions as mentioned in [3], where ES has the possibility to assist search and track radars and EA could benefit the high gain and power antenna of radars.

3. Research questions and scientific challenges.

The PhD project aims to explore how several RF functions can be integrated on a joint waveform and how this flexibility can be utilized in distributed MFRF systems. The ultimate goal of this research is to understand when, how and in which scenarios a joint waveform for MFRF systems could and should be used. This leads to a central research question.

How can MFRF systems combine and trade off RF functions on a joint waveform to obtain operational functionality and flexibility?

The major scientific challenge is to quantify each RF function requirements and understand how these can be combined and traded off on a joint waveform and used in a distributed system. Several types of waveforms have been shown in the literature to combine RF functions, but none have been used to combine radar, communication, electronic warfare and navigation. In addition, there seems to be a lack of studies exploring how the flexibility of a MFRF system can be utilized in a distributed system.

The PhD project is proposed to be divided into three research parts, where each part will answer different nuances of the central research question.

Research part 1 - Theory and quantification of joint waveform

In the first part of the study each fundamental RF function requirements will be quantified. The goal of this research is to gain insight into what makes a good radar, communication, EW and navigation waveform. Based on this common nomenclature, different waveforms modulations will be studied and analyzed to understand its flexibility and trade off capabilities whit regards to all RF functions. Results of this study will be published in a conference paper, marked as paper 1.

Relevant research questions:

- Which RF functions are more suitable to be combined on a joint waveform?
- What are the main challenges when combining several RF functions on a joint waveform?
- What are the tradeoffs for standard waveform modulations, like FMCW, OFDM, DSSS and FBMC, when used as a joint waveform signal?

Research part 2 – Joint waveform in distributed systems

This research part will explore how the increased flexibility of a joint MFRF waveform can be utilized in distributed systems. Whit the ability to adapt to its surroundings and change its role accordingly, a joint waveform can be crucial for maintaining safe and functional operation in scenarios with little or unknown prior information. By analyzing and comparing a distributed system with and without MFRF capabilities, the research will explore if there exist scenarios where MFRF systems outperform systems with fixed RF capabilities. Results of this study will be published in a journal, marked as paper 2.

Relevant research questions:

- In which scenarios does a distributed MFRF system outperform other RF systems?
- What are the general rules of thumbs when designing a distributed MFRF system?
- Which RF functions and flexibility of a joint waveform is beneficial in a distributed MFRF system?

Research part 3 - Concrete application and implementation of joint waveform

Next, based on findings in research part 1 and 2, a concrete concept for a joint waveform MFRF system will be developed. The study will involve simulating and optimizing a joint MFRF waveform suited for implementing on a real-world demonstrator. The theory and simulation of this research part will be published in a conference paper, marked as paper 3. Results and findings from paper 3 will be further analyzed and implemented in a real-world demonstrator. The findings from real-world experiments will be published in a journal marked as paper 4.

Relevant research questions:

- What optimization techniques can be used to optimize a joint MFRF waveform?
- Which challenges do we encounter when implementing a joint MFRF waveform in a real-world demonstrator?
- Does simulation and real-world experiments on MFRF systems match each other?

4. Scientific method.

In the PhD project, the different research parts and papers will answer parts of the central research question. Figure 3 shows how each paper will have different focus areas on theory, real-world experiments, distributed systems and joint waveform. The figure also shows how each paper will contribute to each other (via arrows) and describes the main scientific method each paper will use.

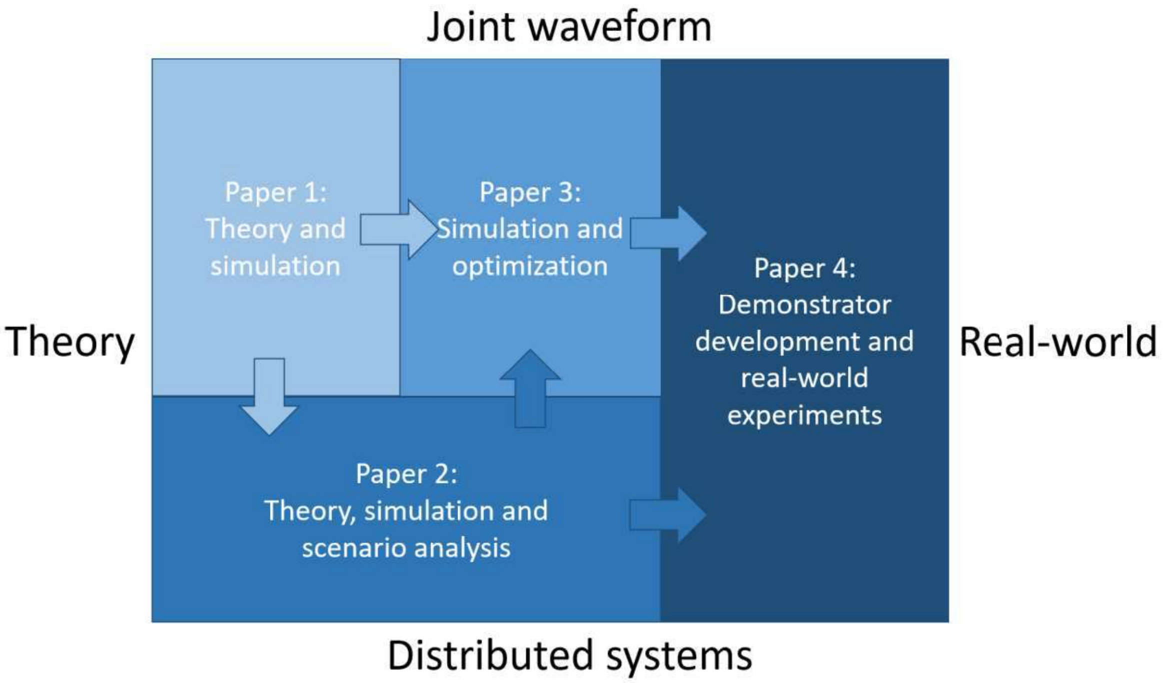

Figure 3: Paper overview, contributions and focus areas

As shown in Figure 3, paper 1 and 2 will focus on theory and simulation and lay the foundation for paper 3 and 4. Paper 3 will simulate and optimize a joint waveform for a concrete application, which will be implemented and tested in a demonstrator using real-world experiments documented in paper 4.

The papers will be published in peer-reviewed conferences and journals. MFRF systems have a broad approach on different RF functions, therefore a wide variety of conferences and journals suit the research topic in this project. Relevant places could be *IEEE Access*, *IEEE Transactions on Radar Systems*, *IEEE International Conference on Phased Array Systems and Technology* or *IEEE Radar Conference* to name a few.

Available hardware and software

To complete paper 1 a simulator software needs to be developed from the ground up. The focus on this simulator will be high level characteristics of different RF functions. Code of separate RF functions are available for use in the project and can be used as a basis for the simulator.

For studying distributed MFRF systems in paper 2 the simulator described in [26] will be used. This simulator needs to be further developed to include MFRF capabilities. When implemented, this simulator will be a good foundation to analyze if distributed MFRF systems can outperform systems with fixed RF capabilities.

The simulator used for paper 1 will be extended to optimize a waveform for the concrete application studied in paper 3. Broadband AESA antennas, filters and different RFSoC hardware from Xilinx, in addition to several software modules, are available to be used in this PhD project. It is likely that some new hardware and software need to be developed for the demonstrator used for paper 4, but this will depend on the concrete application and therefore has not been decided yet.

5. Expected impact.

The PhD project is expected to have an impact on how to approach MFRF systems in future studies. As mentioned, earlier studies often treat MFRF systems as a basis RF function whit some ad-on functionality. This project will aid for a broad approach and define all the possible RF functions that be implemented on a joint waveform.

MFRF systems will use its resources more efficiently and ensure good use of resources. If multiple RF functions can be implemented on a shared hardware, both consumption and production will decrease compared to stand alone systems for each RF function. Therefore, it’s expected that this PhD project will impact Sustainability and Development Goal (SDG) 12 titled "responsible consumption and production".

SDG 11 “sustainable cities and communities” is to make cities and human settlements inclusive, safe, resilient, and sustainable. MFRF systems are expected to have an impact on safe and resilient cities and communities. The flexibility to change its role or function during unexpected events, like disasters or war scenarios, could make MFRF systems crucial for safe operations in the future. Distributed MFRF systems could provide navigation in areas without global navigation system coverage, they could search for people or objects using radar or ES capability and provide local ad-hoc communication for safe operation.

MFRF systems are also expected to have an impact on SDG 3 “good health and well being”. Internet of Things (IoT) enabled health is expected to have a huge impact on ensuring good healthy lives and promote well-being for all at all ages. Today's IoT sensors often include one RF function, but future IoT sensors could also be MFRF systems. Indoor communication could provide navigation and information for healthcare robots. The same waveform could monitor patients' rooms and measure vital health parameters like breathing frequency as a radar. Distributed MFRF IoT sensors could collaborate and prioritize functions that promote human – machine teaming in healthcare.

6. Ethics.

How MFRF systems prioritize and choose different RF functions could have ethical implications. In traditional RF systems operators often have control and decide how and when each function should operate. If decisions are made by computers and moved further away from humans, we need to make sure they follow guidelines and policies set by humans. Therefore, we aim to develop explainable systems with expert judgment where simulations will be validated by testing whit known theory and real-world experiments.

Real world experiments whit MFRF systems will involve transmitting electromagnetic energy in a frequency band. The project team will ensure that all electromagnetic radiations will be in accordance with regulations set by the Norwegian Communications Authority (Nkom). Electromagnetic energy collected in the project will not include descriptive data that could identify objects of persons and potentially violate their privacy.

9. Cooperation with external parties.

No external partner is planned to contribute to the project. However, there might be initiatives and collaboration forums, e.g. established NATO groups, at FFI that might find this research interesting. In this case, collaboration will most likely be in the form of knowledge transfer or assistance.

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