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Modular Design Method Considering System Architecture in Maritime Radar System for Autonomous Ship

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INCOSE International Symposium 2025 | Ottawa, Canada

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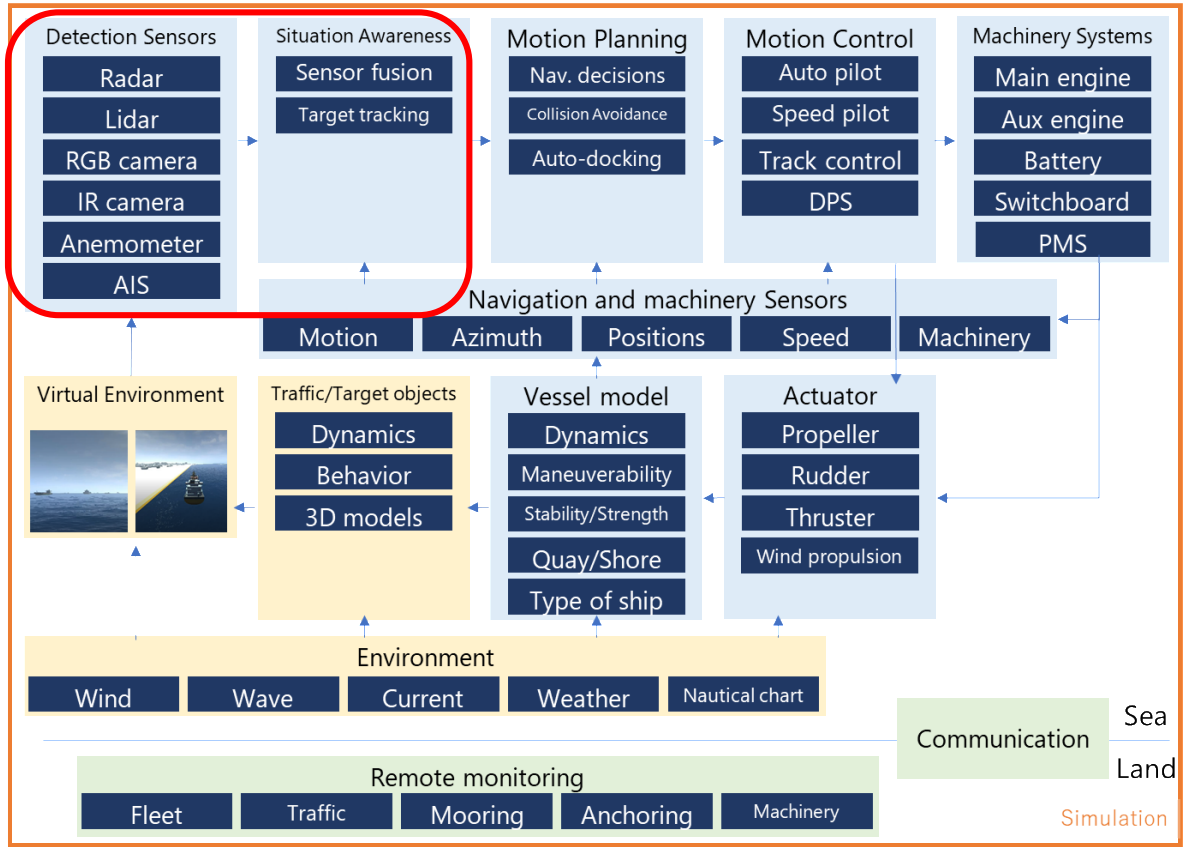
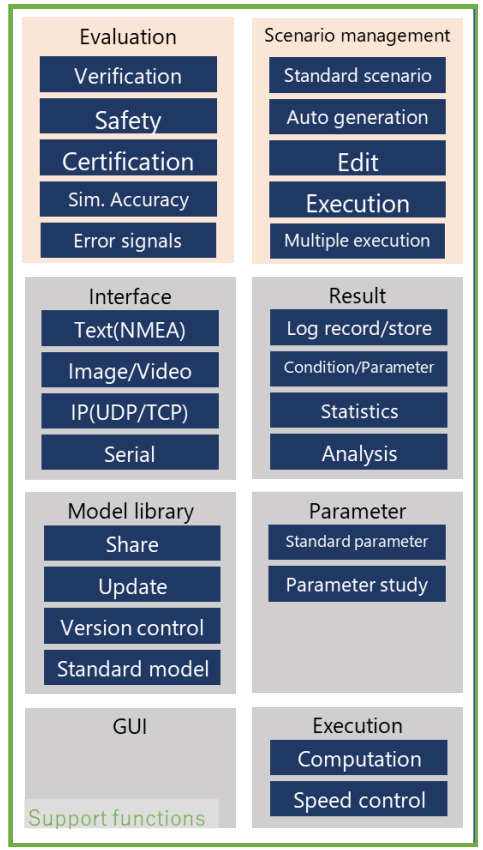
Research Background: System Configuration of an Autonomous Ship

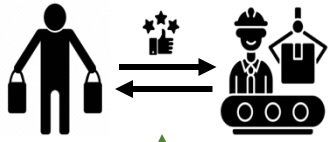




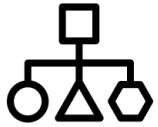
出典：FURUNOのHP

Research Background

Demand for Product Customization



Product Modularity



Versatility of Product Modularity

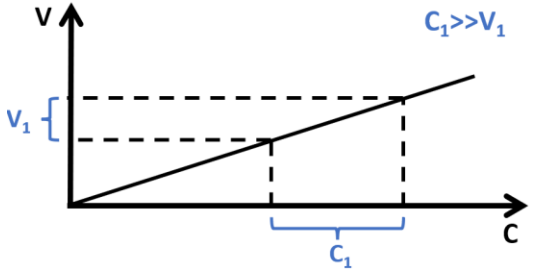
Why Modularity?

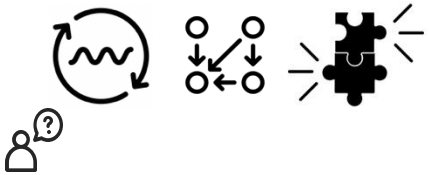
Why Radar?

Importance of Radar Systems in **Autonomous Ships**

15 billion dollars by 2030, with over 1,000 vessels planned for deployment

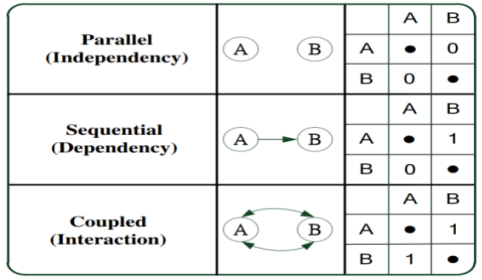
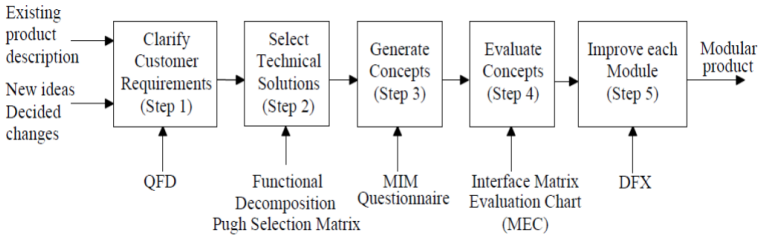
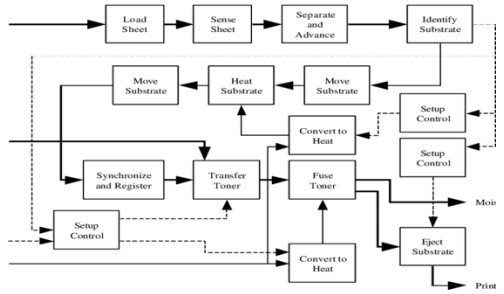
Challenges of Modularization in Radar Systems





Exploring Modularization in Radar Systems.

Literature Review

	Design Structure Matrix (DSM)	Modular Function Deployment (MFD)	Function Structure Heuristics (FSH)
Figure			
Main idea	DSM: Visualizes interdependencies among elements in system. It groups functions and components to optimize internal interactions while minimizing cross-group dependencies.	MFD: Covers more areas than other methods, it provides a clearer picture of which modules to integrate or separate and how to allocate resources through matrixes.	FSH: This method quickly breaks down a product into subfunctions or parts, providing a rough overview of interactions.
Drawback	It lacks systematic evaluation, profitability assessment, and alternative generations for achieving modularization objectives.	Significant amount of time required for initial implementation and usage, as it necessitates mapping the entire process.	It does not provide enough information about product, and it is difficult to use it with complex system.

Originalities of proposed approach:

1. Evaluate performance variations of the product while considering modularity
2. Quantify complexity of the interrelationships and modules more systematically

Research Motivation and Objectives

Motivation: Modularizing radar is challenging, prompting the development of a method specifically tailored for such complex products, with a focus on systematic evaluation and assessment aligned with modularization objectives.

Main objective : This research aims to propose a modular design that includes fewer modules with wider radar variation.

Sub objective #1: Enhance the manageability of radar systems by dividing them into separate modules, thereby reducing assembly time and simplifying maintenance procedures.

Issues to be solved:

Issue #1: Customizing radar systems for varying requirements is challenging.

Issue #2: Radar system manageability is limited due to the higher complexity.

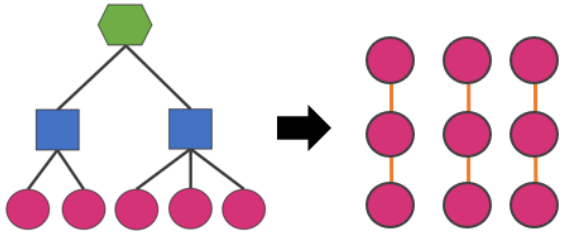
Contents

Research approach

Decomposition

Break down product into components

Build product family



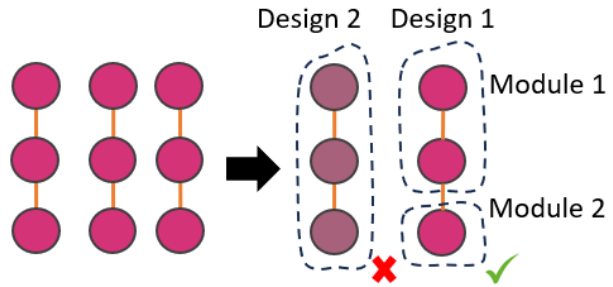
Decomposing product into components

Integration

Generate various modular designs

Define calculation indices

Determine optimal modular designs



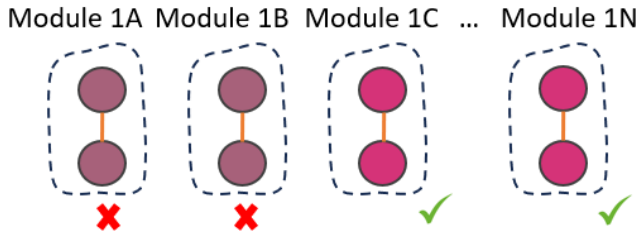
Integrating components into modules

Evaluation

Define performances and module variations of product families

Evaluate modular designs

Extract best design on each family product

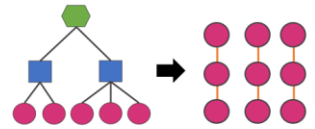


Evaluate module variation

Contents

Main functions of pulsed radar

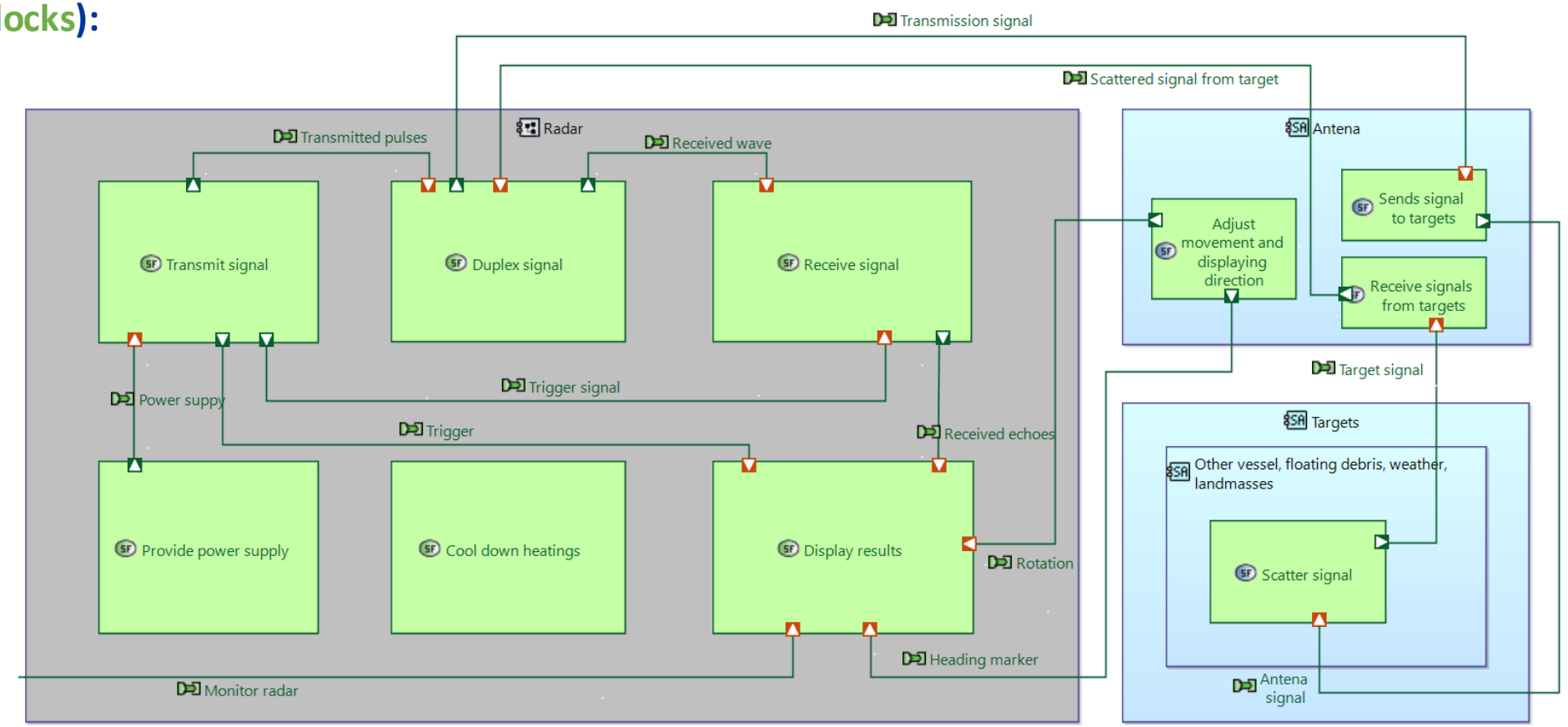
Determined main functions of the pulsed radar in Capella system architecture tool.



Decomposing product into components

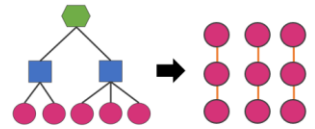
Main functions (Green blocks):

- Transmit signal
- Duplex signal
- Receive signal
- Display results
- Cool down heating
- Provide power



Sub functions

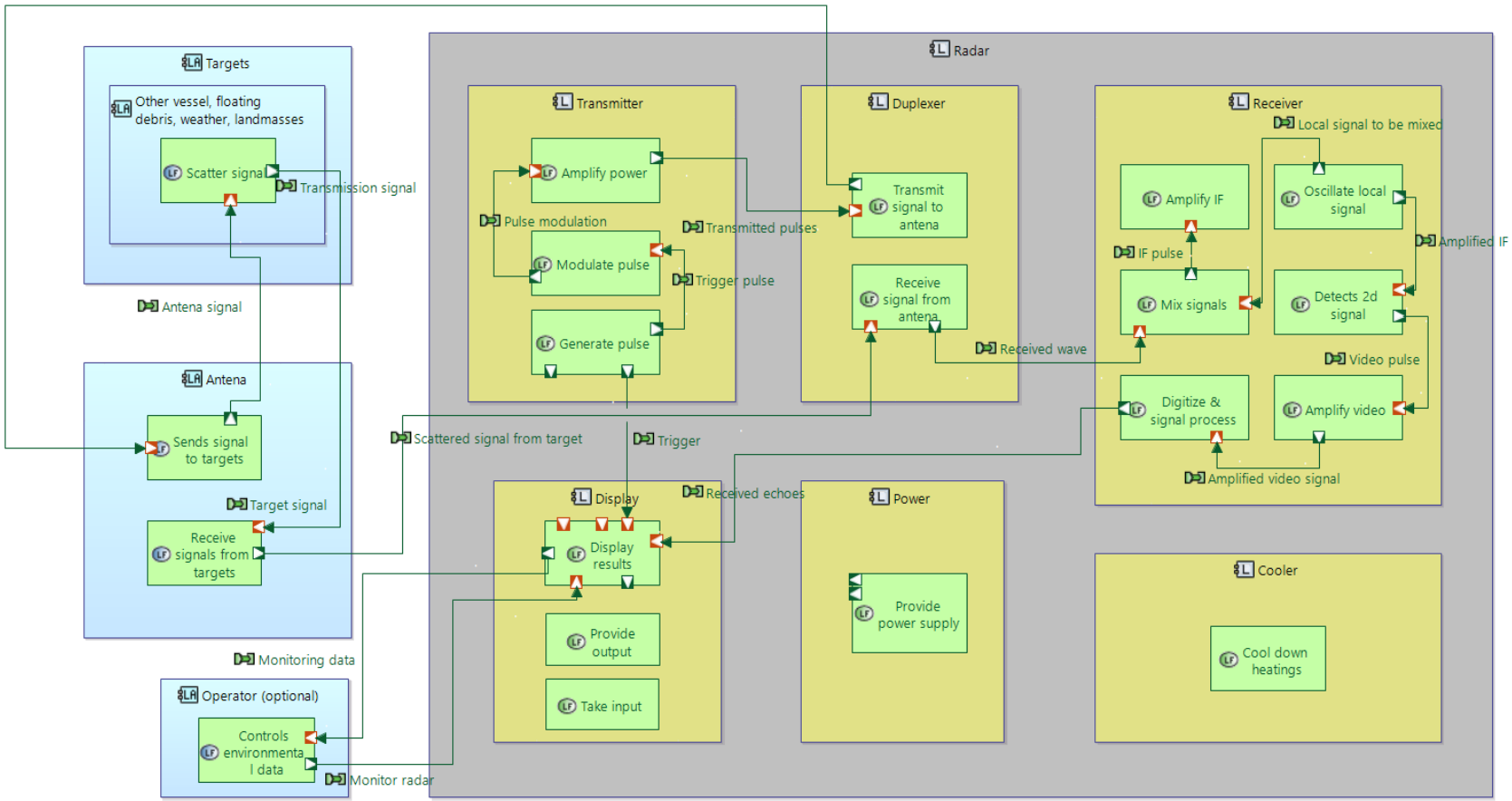
Main functions have been divided into sub-functions.



Decomposing product into components

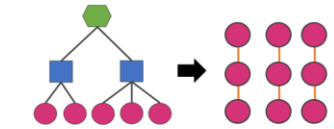
Sub functions (Green blocks):

- Amplify power
- Modulate pulse
- Pulse generator
- Transmit signal
- Cool down heating
- Provide power
- Amplify video
- Digitize signal
- Amplify IF
- Generate local signal
- Mix signal
- Detect signal
- Supply power
- Send signal to target
- Display results
- Receive signal from targe
- Receive signal

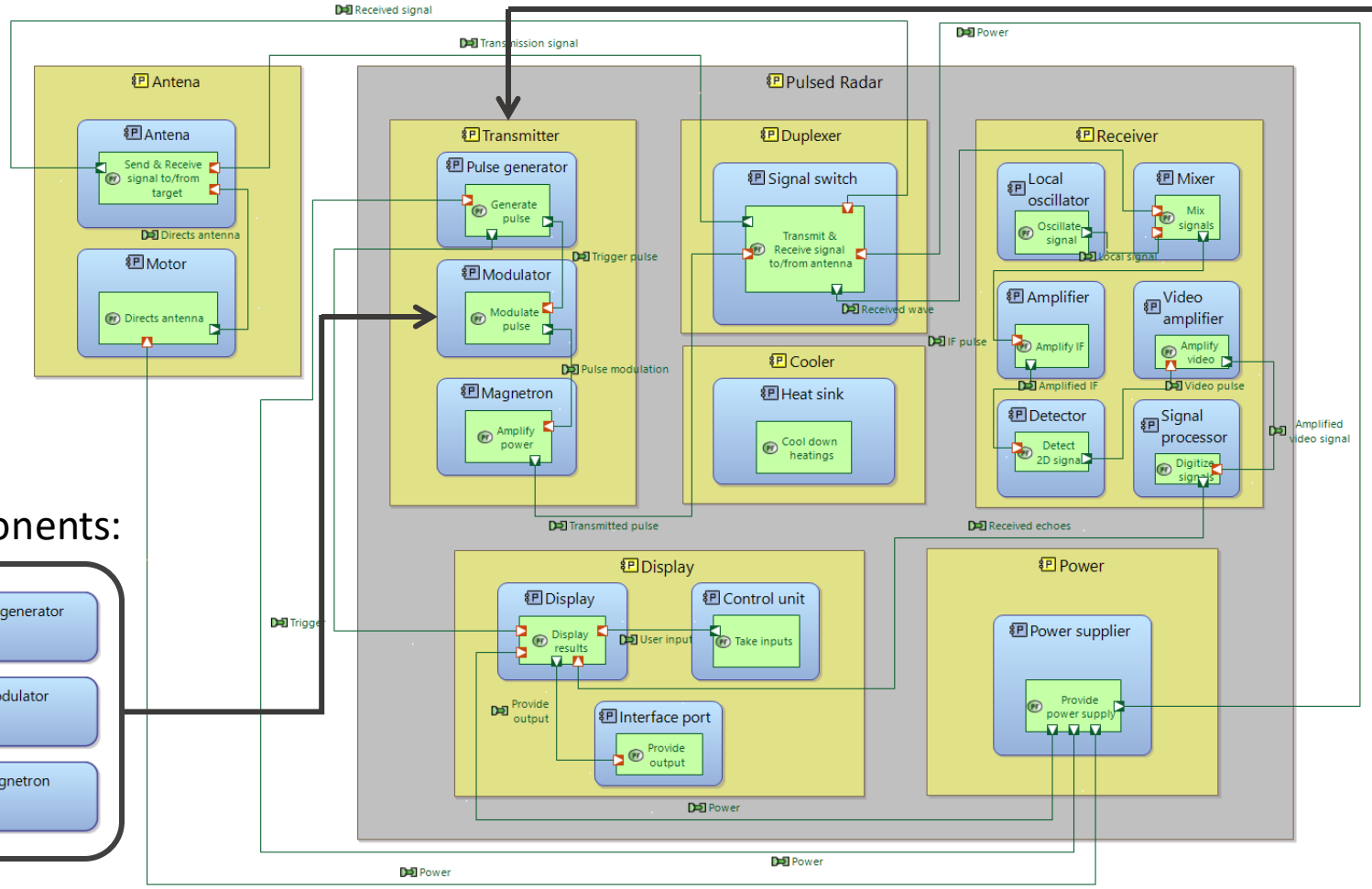


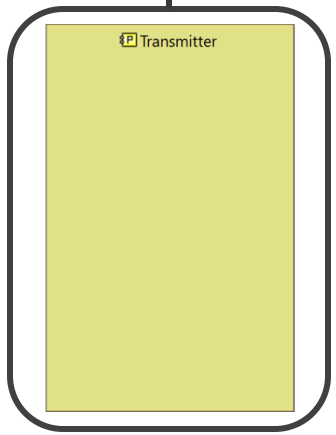
Physical components

Sub-functions turn into physical component, yellow blocks represent physical element of main functions.



Decomposing product into components





Transmitter: physical part of main function current pulsed radar

Components:

Total components:17

Main functions of pulsed radar

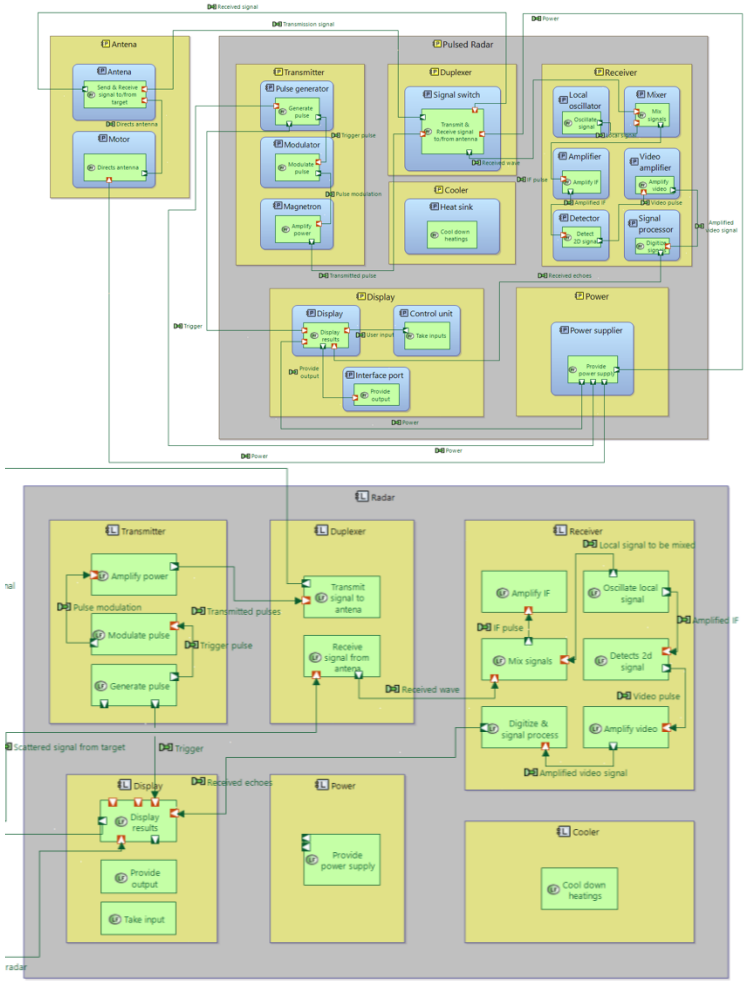
Product families:

X-band radar 1 (X1)
X-band radar 2 (X2)
X-band radar 3 (X3)

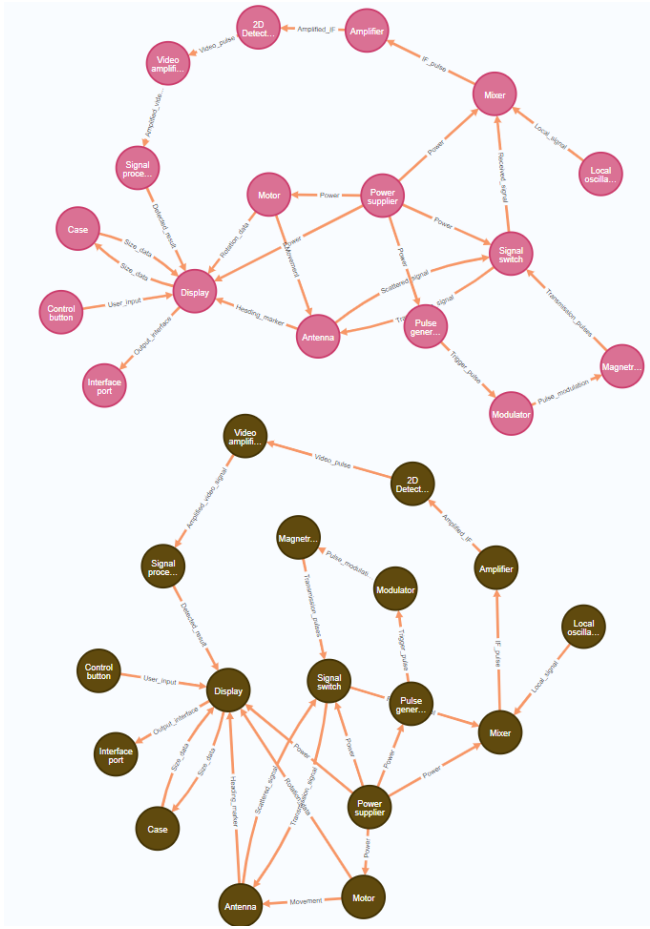
S-band radar 1 (S1)
S-band radar 2 (S2)
S-band radar 3 (S3)

	Freq [GHz]	Range
X band	8-12	Short
S band	2-4	Long

Capella diagram:

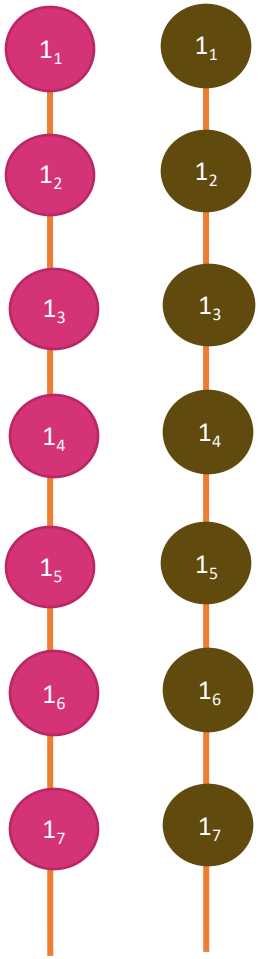


Real network:



Neo4J

Simple network:

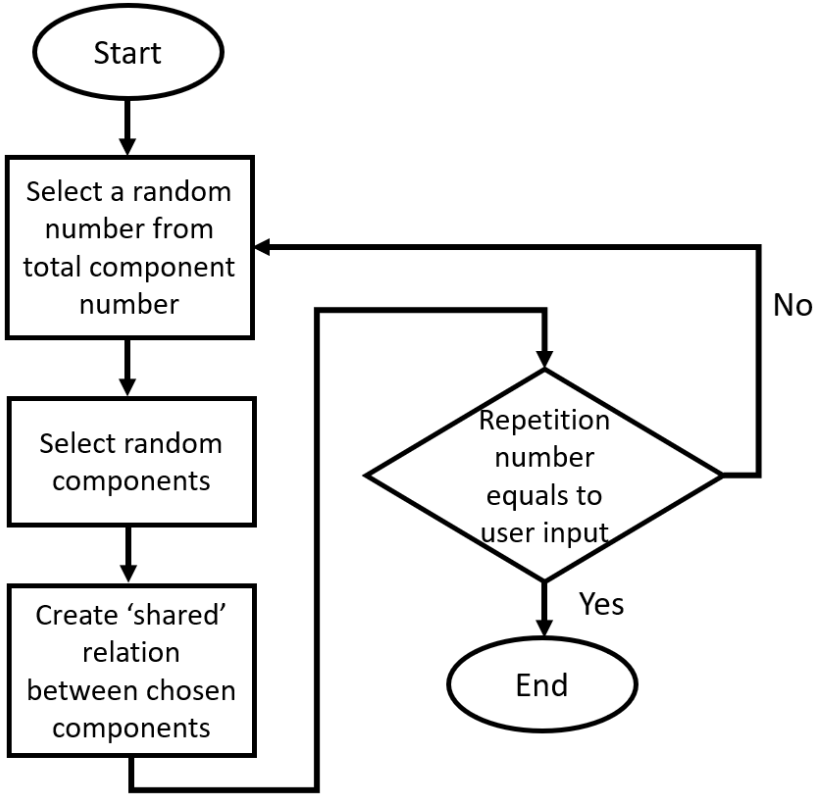


Main

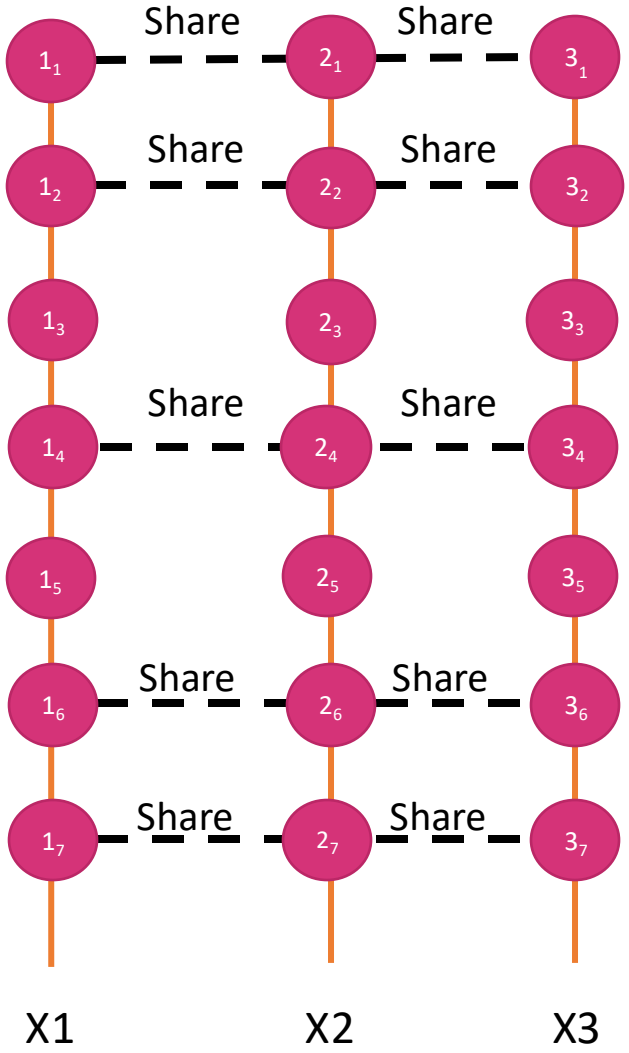
Contents

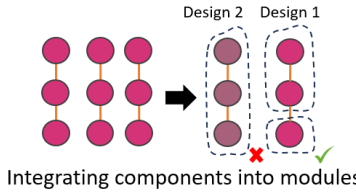
Random generation of share relations

Algorithm of generating share relations:

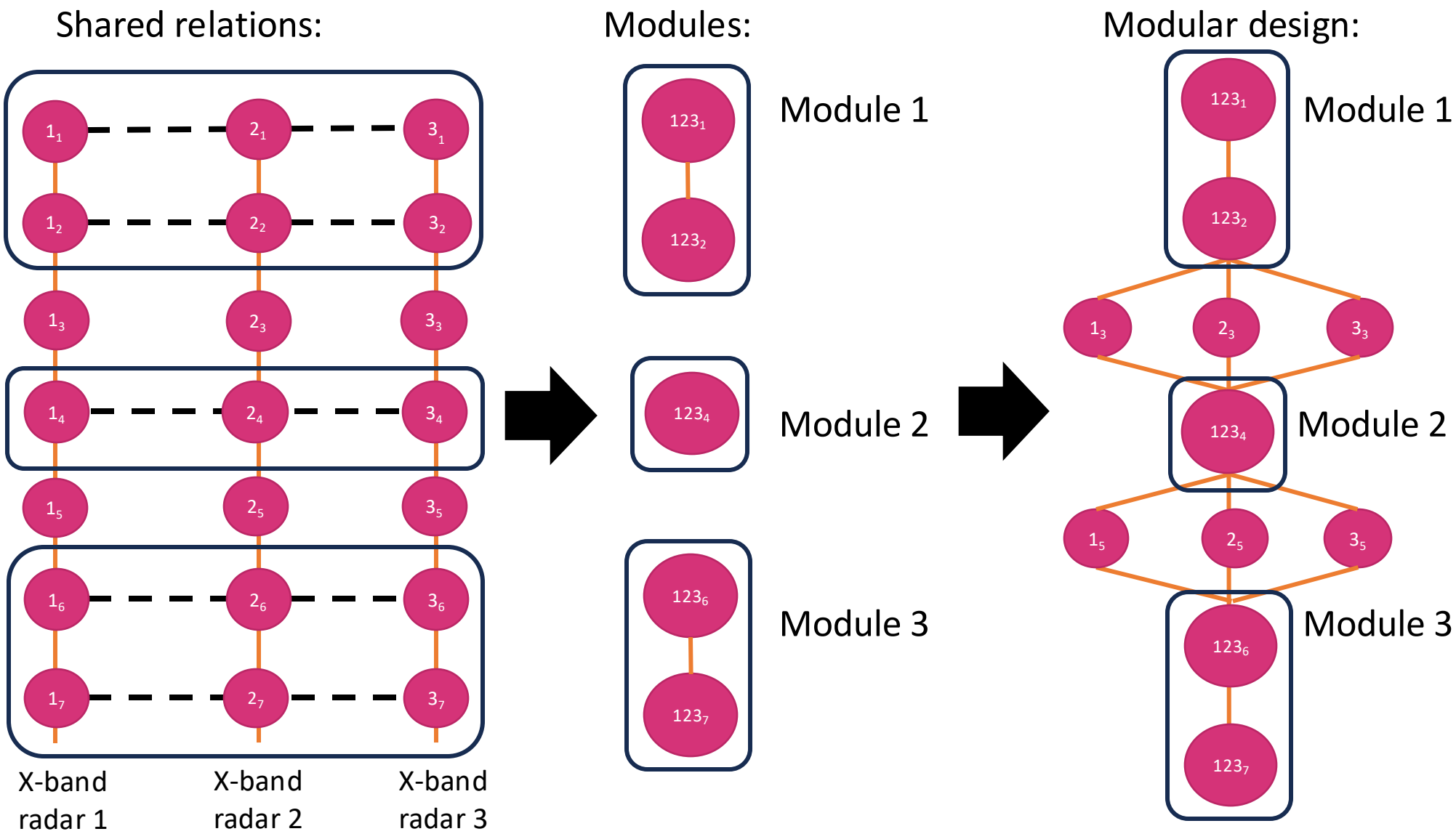


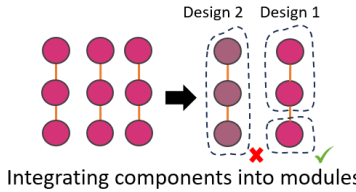
Selected random component:5





Modules and modular designs





Calculation indices

In this research, we have defined four evaluation indices. Difficulty is dependency level between the elements such as parameters and performances.

$$RD = (CD_i + CDj) \sum_{k=1}^{N_i} \sum_{l=1}^{N_j} pac_{kl}$$

CD_i-Component difficulty of the i th component
CD_j- Component difficulty of the j th component

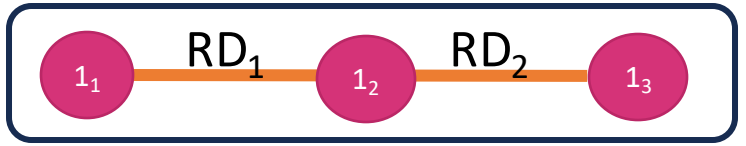
pac_{kl}- Correlation coefficient between k th parameter of the i th component and l th parameter of the j th component

N_i- Number of parameters in the i the component
N_j- Number of parameters in the i the component

1. Module Inner Difficulty → Max (Inner difficulties of modules)

$$DOD = \sum_{i=1}^{N} RD_i$$

Module 1:

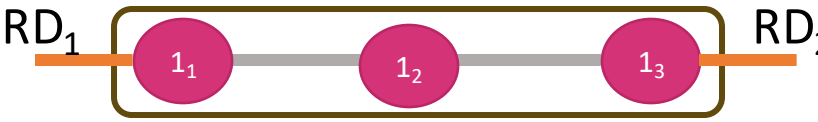


$$DID = \sum_{j=1}^{N} \sum_{i=1}^{n} RD_{ij}$$

RD- Relation difficulty in the module
DID- Design inner difficulty

2. Module Outer Difficulty → Min (Outer difficulties of modules)

Module 1:

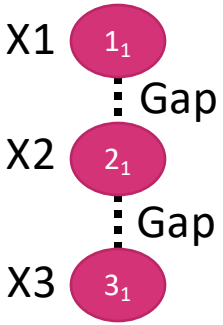


$$DOD = \sum_{i=1}^{N} RD_i$$

RD- Relation difficulty outside the module
DOD- Design outer relation difficulty

Calculation indices

3. Gap→ Min (Gap between parameter's impact value and desired performances)

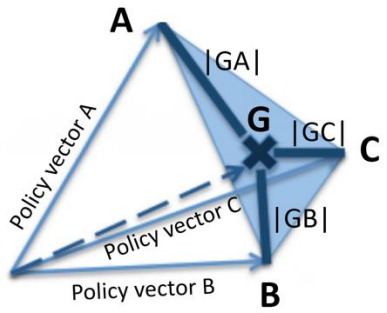


	Performances: Requirement vector of X band radar 1	Parameter's impact values: Impact vector: Parameter: Pulse width
Range accuracy	9	5
Range discrimination	9	3
Bearing discrimination	9	5
Measurement stability	1	3
Maximum range	1	1
Environmental clutter control	1	1

Policy vector A = $\begin{pmatrix} 9 & & 5 \\ 9 & & 3 \\ 9 & * & 5 \\ 1 & & 3 \\ 1 & & 1 \\ 1 & & 1 \end{pmatrix}$

$$DG = \sum_{j=1}^{N} \sum_{i=1}^{n} \sum_{k=1}^{m} PG_{ijk}$$

PG- Parameter gap
m – Number of parameters in the component
n – Number of components in the module
N – Number of modules in the design
DG- Design gap

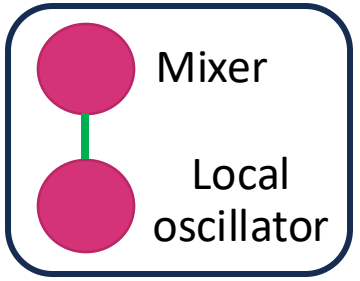


$PG = |GA| + |GB| + |GC|$

4. Design Conflict → Min (Comparison of modules with physical parts)

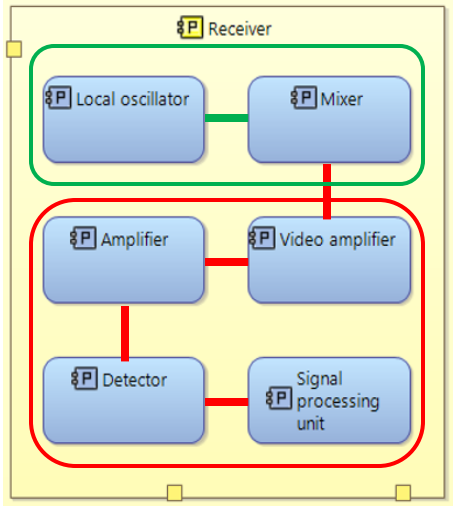
$$EX: DRC = \frac{4}{-} = 4$$

Module 1



Comp: $EX: DCC = \frac{4}{2} = 2$

Rel: $EX: DRC = \frac{4}{1} = 4$



$$MC = \left(DCC \sum_{i}^{N} CD_i\right) + \left(DRC \sum_{i}^{N} RD_i\right)$$

$$DC = \sum_{i=1}^{n} MC_i$$

N – Number of components and relations not in module

DRC- Degree of relation conflict
MC- Module conflict
DCC- Degree of component conflict
DC- Design conflict

Optimal modular designs

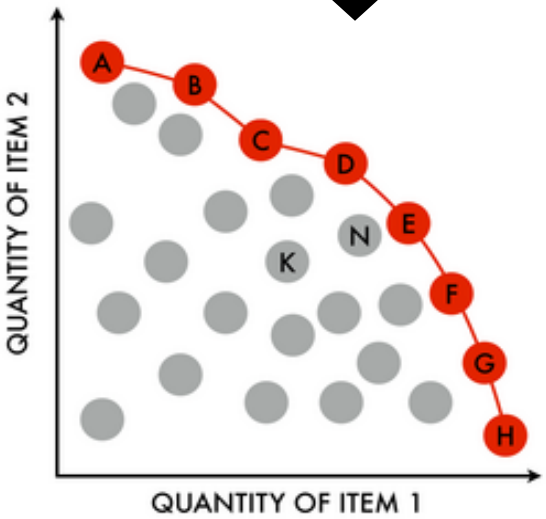
Objective 1: Module Inner Difficulty → Max

Objective 2: Module Outer Difficulty → Min

Objective 3: Gap→ Min

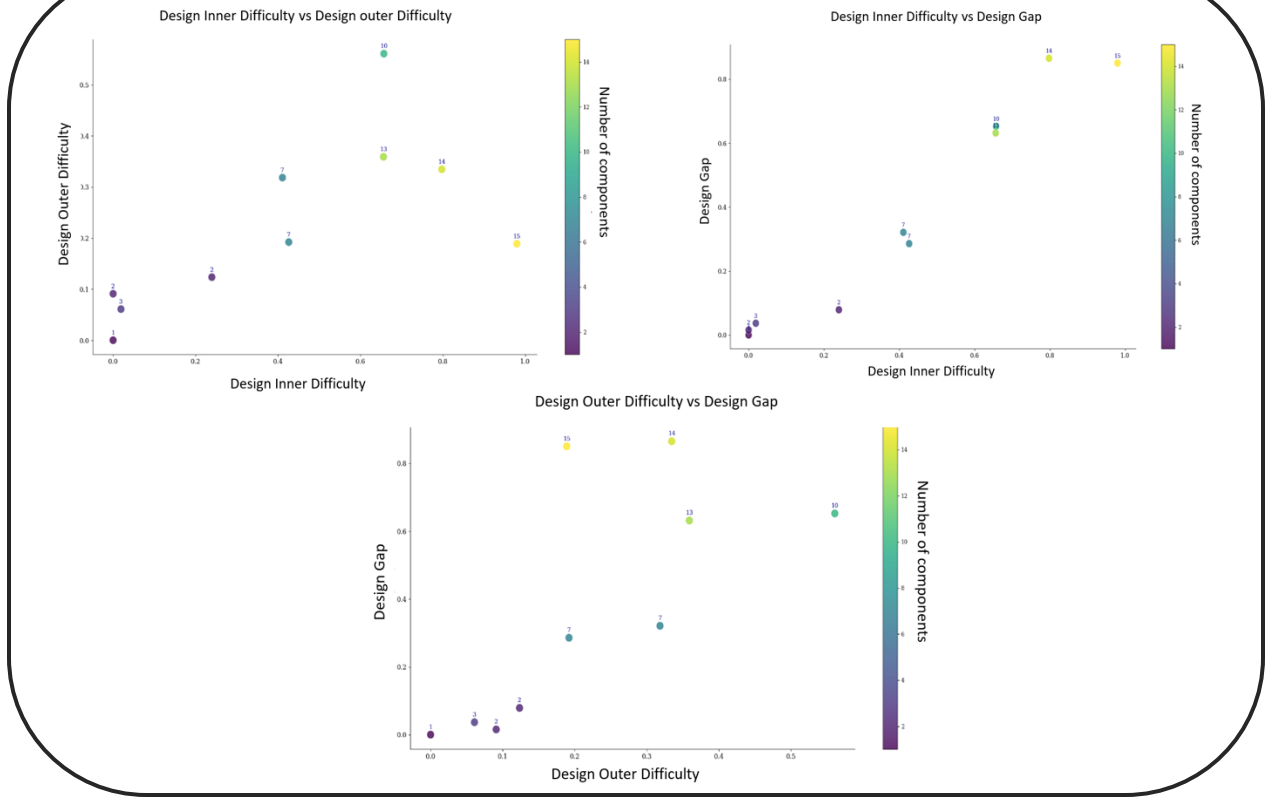
Objective 4: Conflict → Min

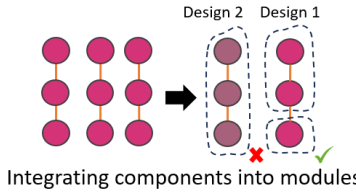
Multiple-Objective Problem



5000 Random modular designs

35-50 Pareto modular designs





Integrating components into modules

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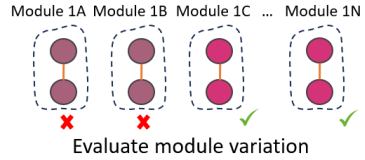
X-band radar: X1, X2, X3



These radars are modularity targets and performances are being used as a reference values.

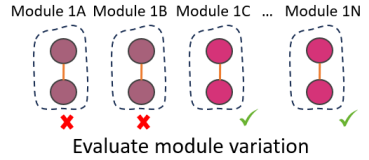
	X1	X2	X3
Range accuracy [m]	2.5	2.7	3
Range discrimination [m]	15	23	33
Bearing discrimination [deg]	0.27	0.41	0.5
Measurement stability	0.77	0.87	0.95
Measurement range [km]	21	42	100
True tracking probability	0.94	0.98	0.99

These performances are configured in the Radar Designer Application, Matlab.

X1 Setting parameters

X-band radar 1

	X1
Range accuracy [m]	2.5
Range resolution [m]	15
Bearing discrimination [deg]	0.27
Measurement stability	0.77
Measurement range [km]	21
Environment clutter control	0.94

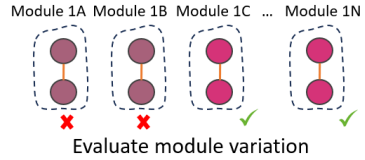


Parameter setting of X1:

Component names	Pulse generator		Magnetron	Modulator	2D Detector	Mixer	Amplifier
Parameter name	PRF [kHz]	Pulse bandwidth [Mhz]	Peak power [kW]	Pulse width [us]	Number of cell	IM freq band [Mhz]	Custom Loss [db]
Value	7	10	1.5	0.2	10	20	5

X2 Setting parameters

X-band radar 2



	X2
Range accuracy [m]	2.7
Range resolution [m]	23
Bearing discrimination [deg]	0.41
Measurement stability	0.87
Measurement range [km]	42
Environment clutter control	0.98

Parameter setting of X2:

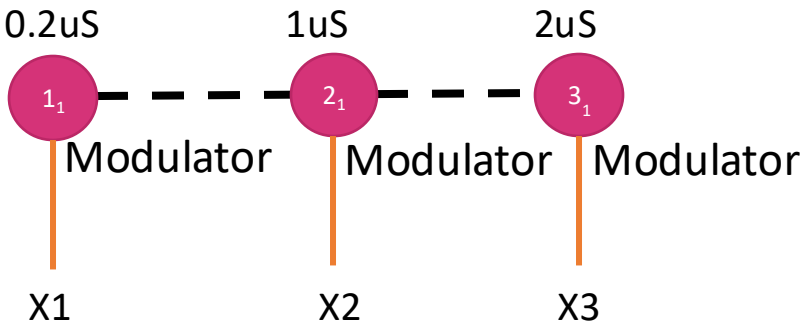
Component names	Pulse generator		Magnetron	Modulator	2D Detector	Mixer	Amplifier
Parameter name	PRF [kHz]	Pulse bandwidth [Mhz]	Peak power [kW]	Pulse width [us]	Number of cell	IM freq band [Mhz]	Custom Loss [db]
Value	3.5	6.5	2	1	15	25	6.5

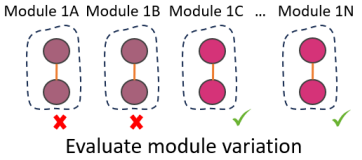
X3 Setting parameters

X-band radar 3

	X3
Range accuracy [m]	3
Range resolution [m]	33
Bearing discrimination [deg]	0.5
Measurement stability	0.95
Measurement range [km]	100
Environment clutter control	0.99

EX: Peak power parameter→ Modulator variation



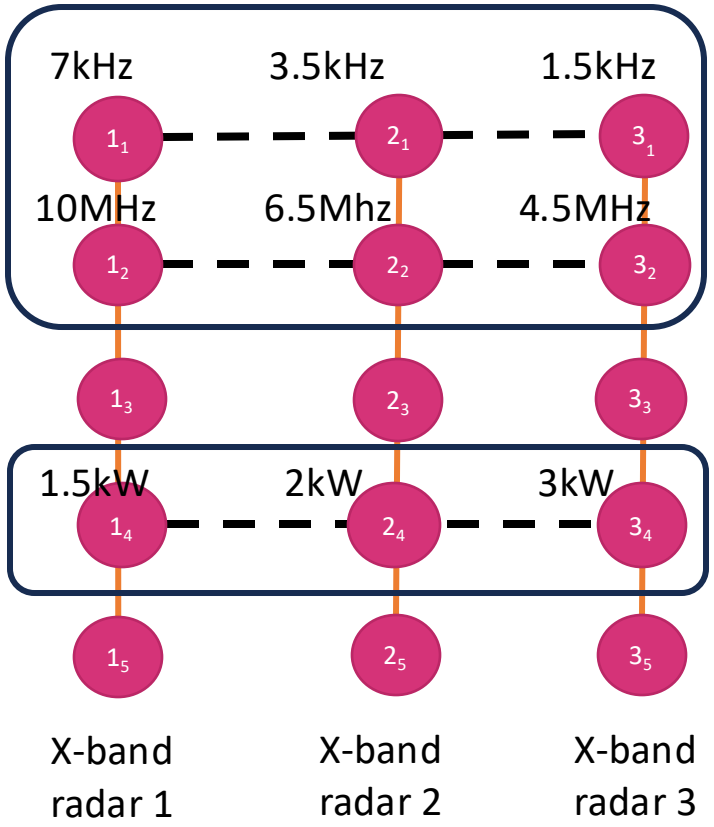


Parameter setting of X3:

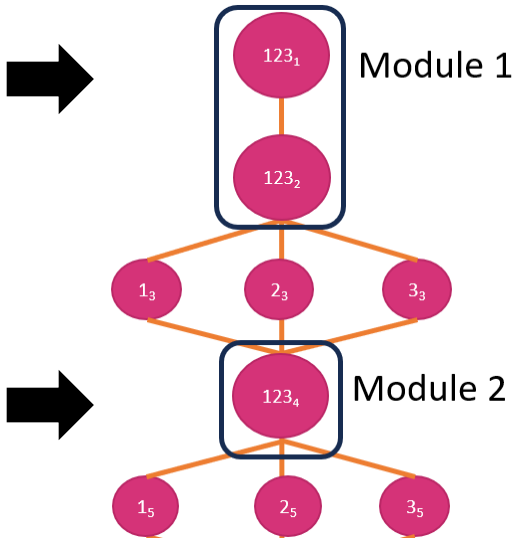
Component names	Pulse generator		Magnetron	Modulator	2D Detector	Mixer	Amplifier
Parameter name	PRF [kHz]	Pulse bandwidth [Mhz]	Peak power [kW]	Pulse width [us]	Number of cell	IM freq band [Mhz]	Custom Loss [db]
Value	1.5	4.5	3	2	20	30	6

Modules and modular designs

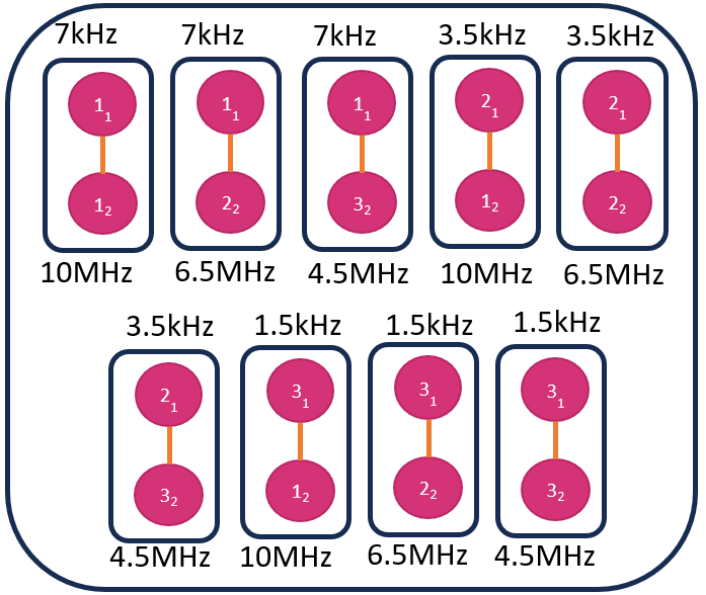
Component variations:



Modular design:

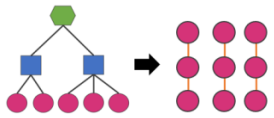


Module 1 variations:



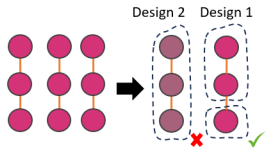
Module 2 variations:

Decomposition:



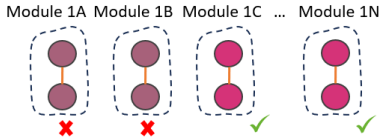
Decomposing product into components

Integration:



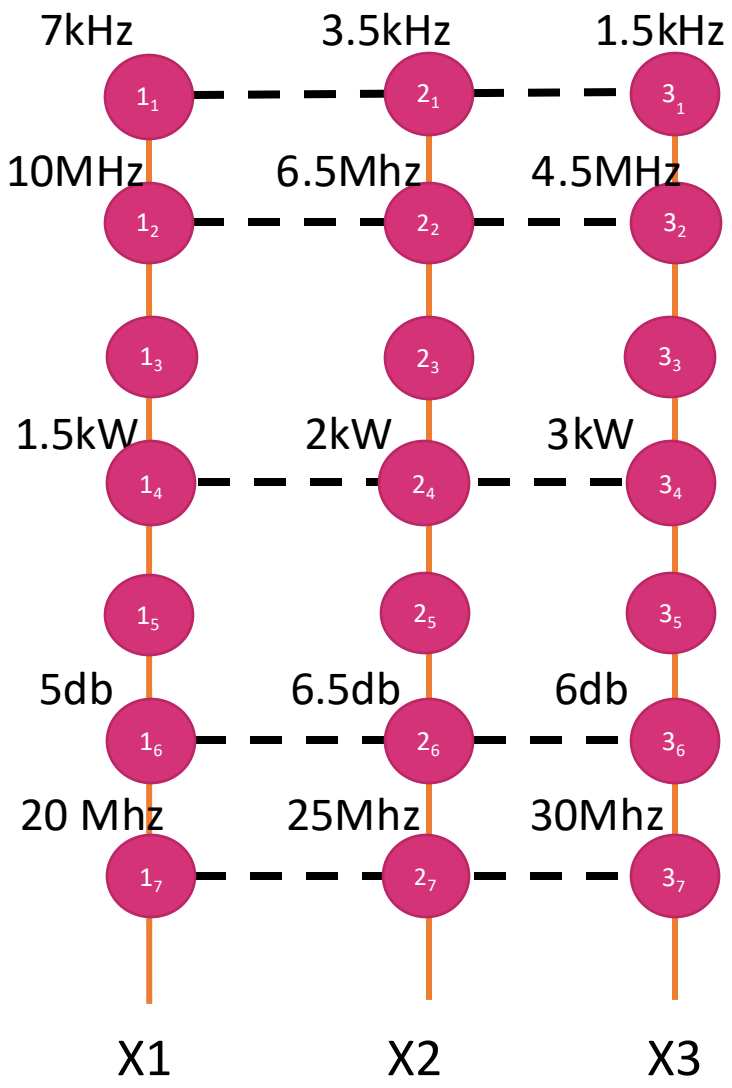
Integrating components into modules

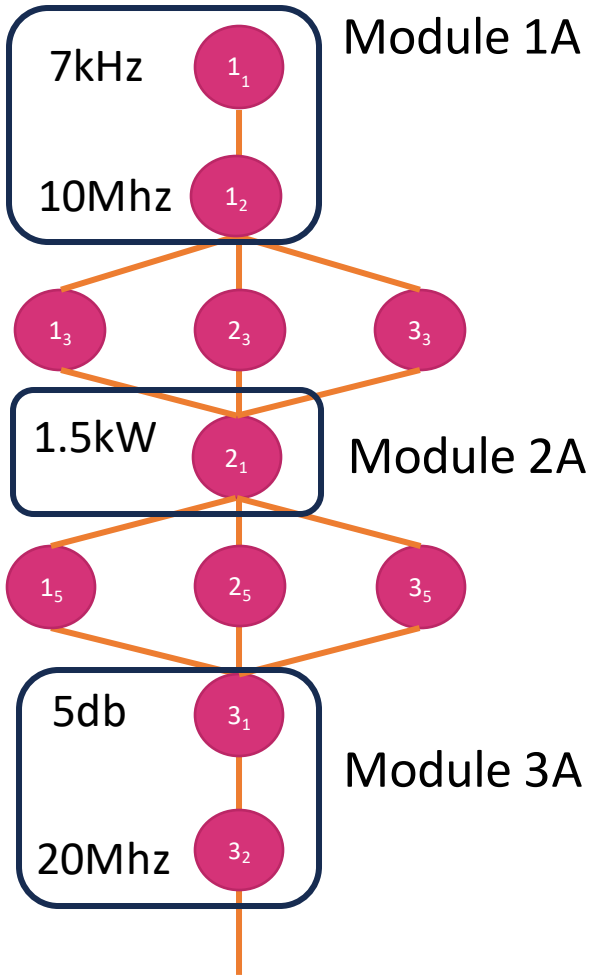
Evaluation:

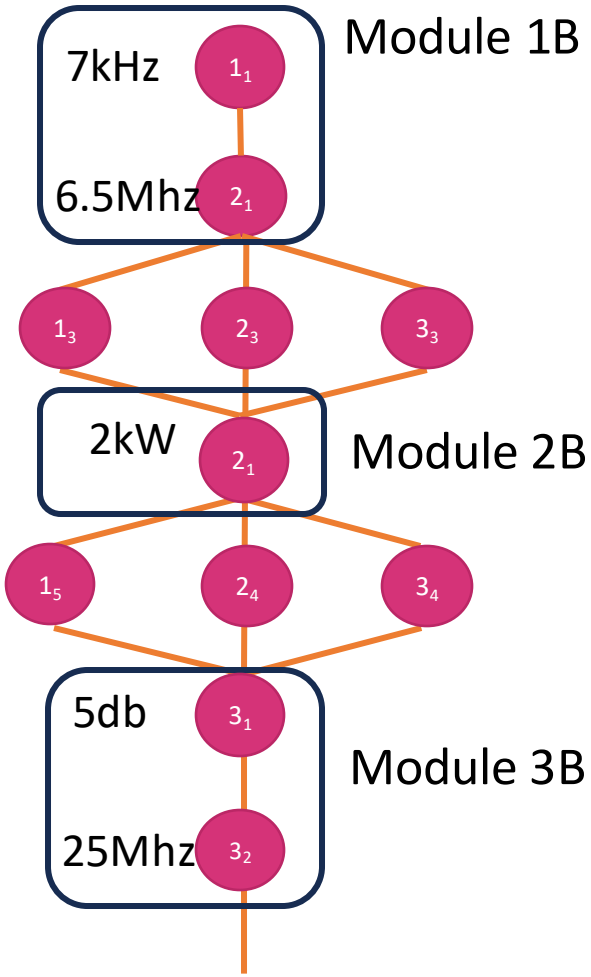


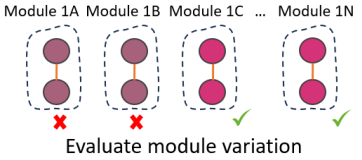
Evaluate module variation

Modules and modular designs









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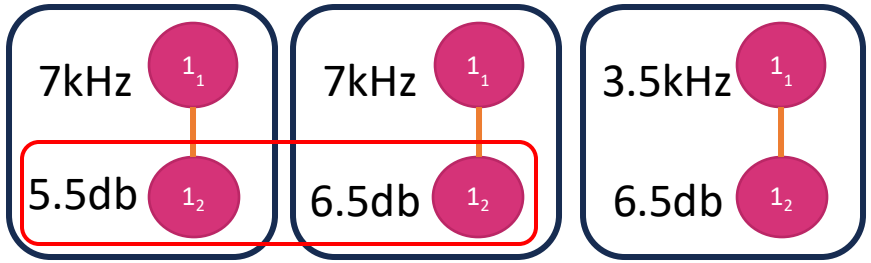
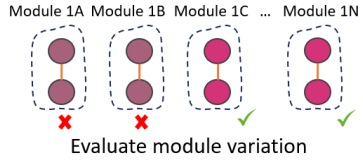
Evaluation with Radar Designer Tool, Matlab

1. Prioritizing the diverse designs in terms performances

Design 1 ✓
Design 2 ✖
Design 3 ✓



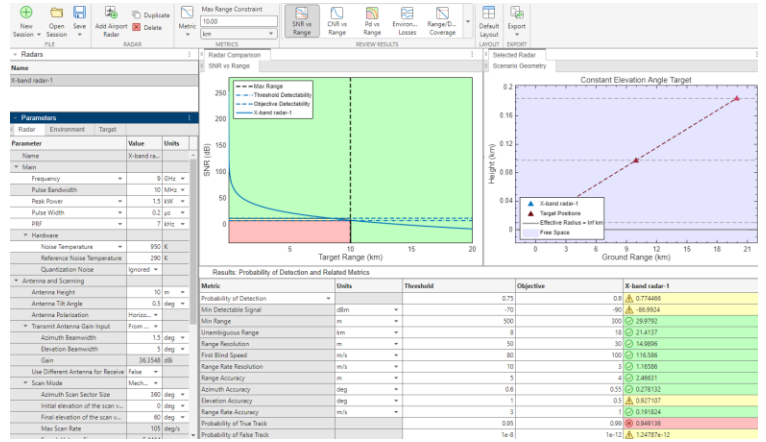
Performances	Design 1	Design 2	Design 3
Range accuracy [m]	2.36	2.36	5.2
Range resolution [m]	21.4	21.3	22.3
Bearing discrimination [deg]	0.4	0.4	0.78
Measurement stability	0.89	0.85	0.64
Measurement range [km]	37.47	37.45	42.6
True tracking probability	0.98	0.96	0.83



2. Choosing performances that meet pulsed radar requirements.

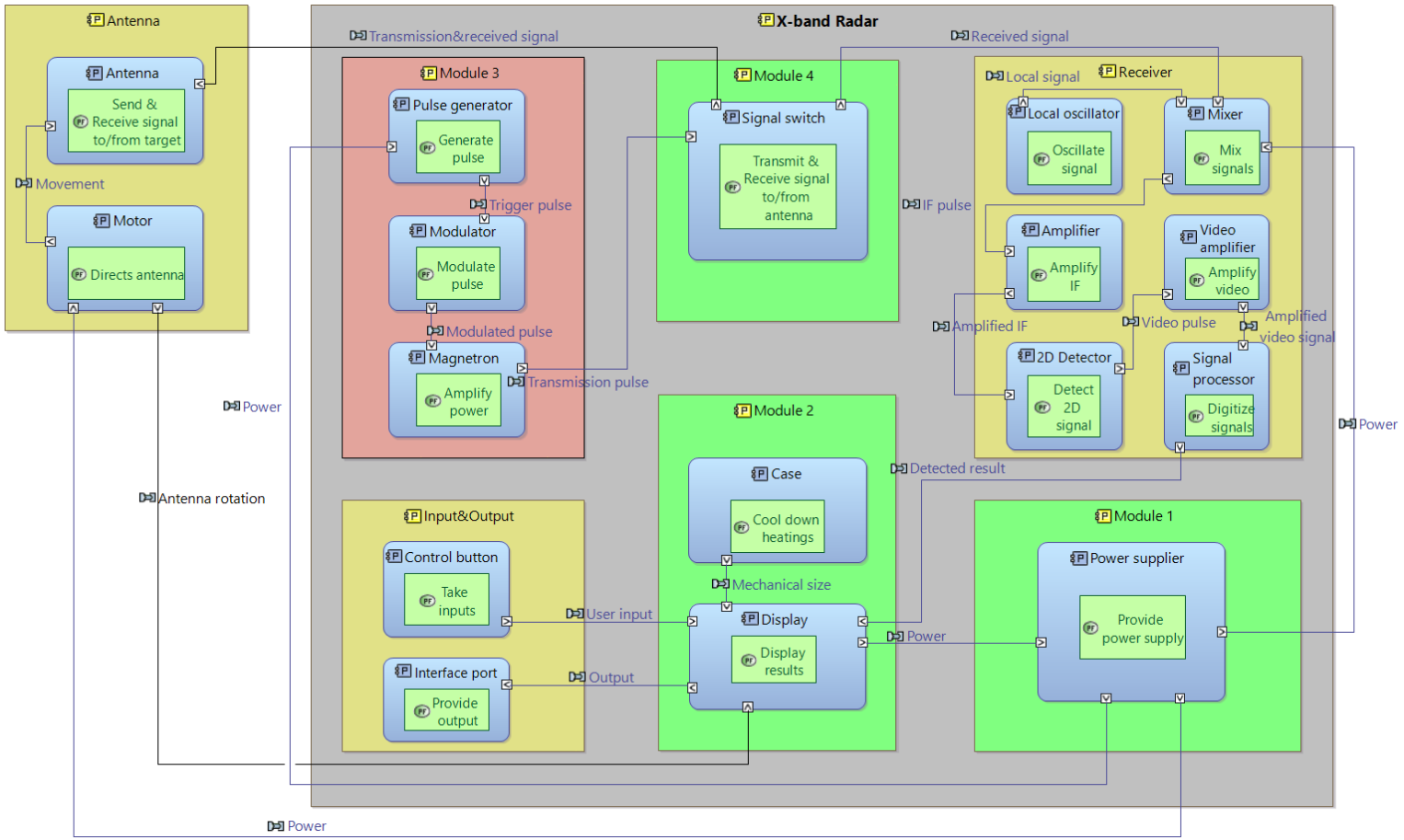
Pulsed radar system **range accuracy** and **bearing discrimination** requirements should be:

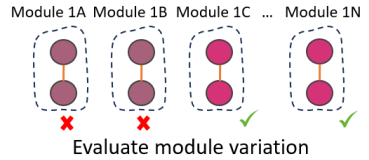
- Range accuracy - within **30 m**
- Bearing discrimination- within **1°**



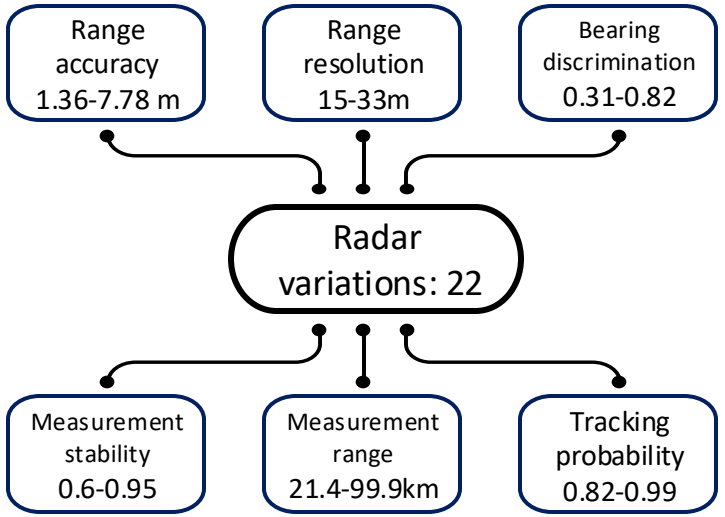
Optimal design for X-band radar

Best modular design for X-band radar:

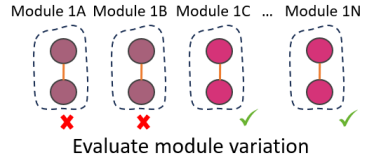




Modules	Component	Module Variation
Module 1	Power supplier	1
Module 2	Display, Case	1
Module 4	Signal switch	1
Module 3	Pulse generator, Modulator, Magnetron	28/22



S-band radar: S1, S2, S3



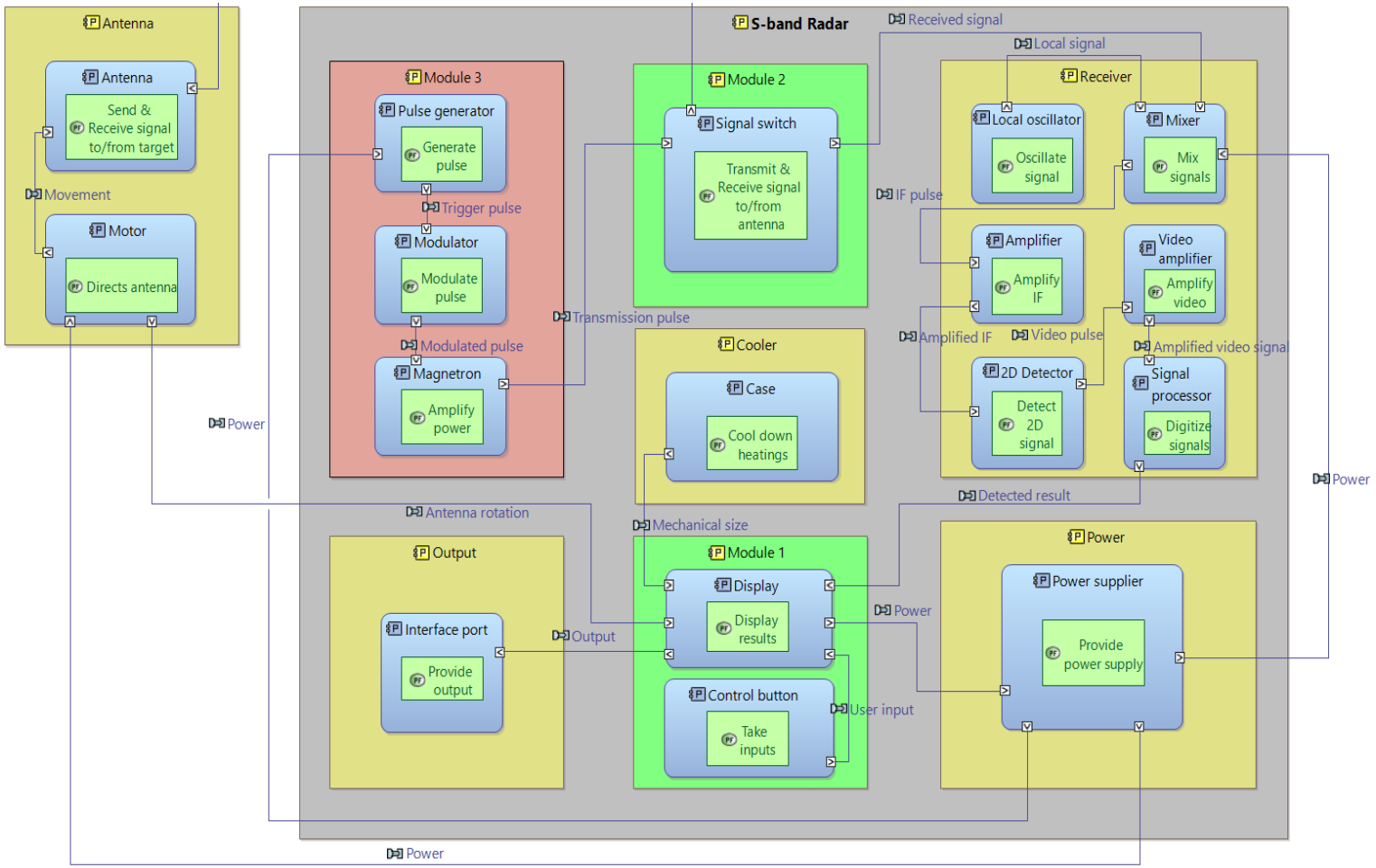
S-band radars work well with longer distances.

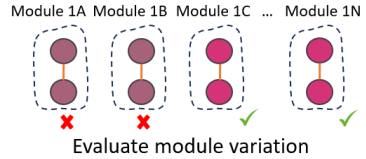
	S1	S2	S3
Range accuracy [m]	5	15	25
Range resolution [m]	50	100	150
Bearing discrimination [deg]	0.25	0.42	0.56
Measurement stability	0.81	0.85	0.9
Measurement range [km]	150	250	350
Environment clutter control	0.96	0.98	0.99

These performances are configured in the Radar Designer Application, Matlab.

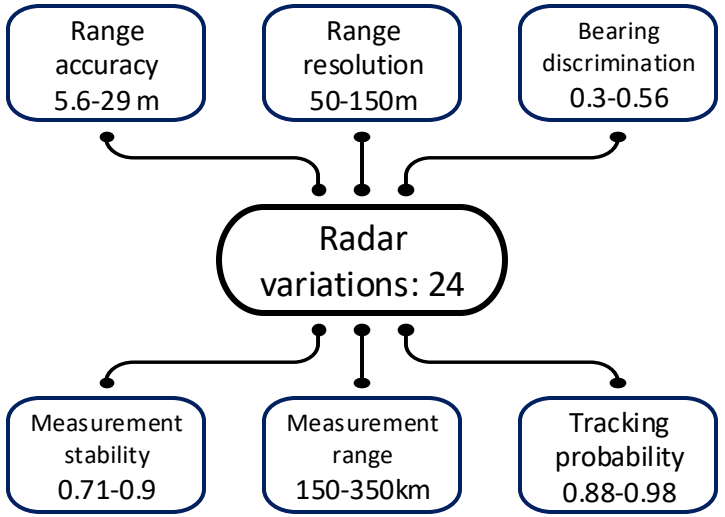
Optimal design for S-band radar

Best modular design for S-band radar:



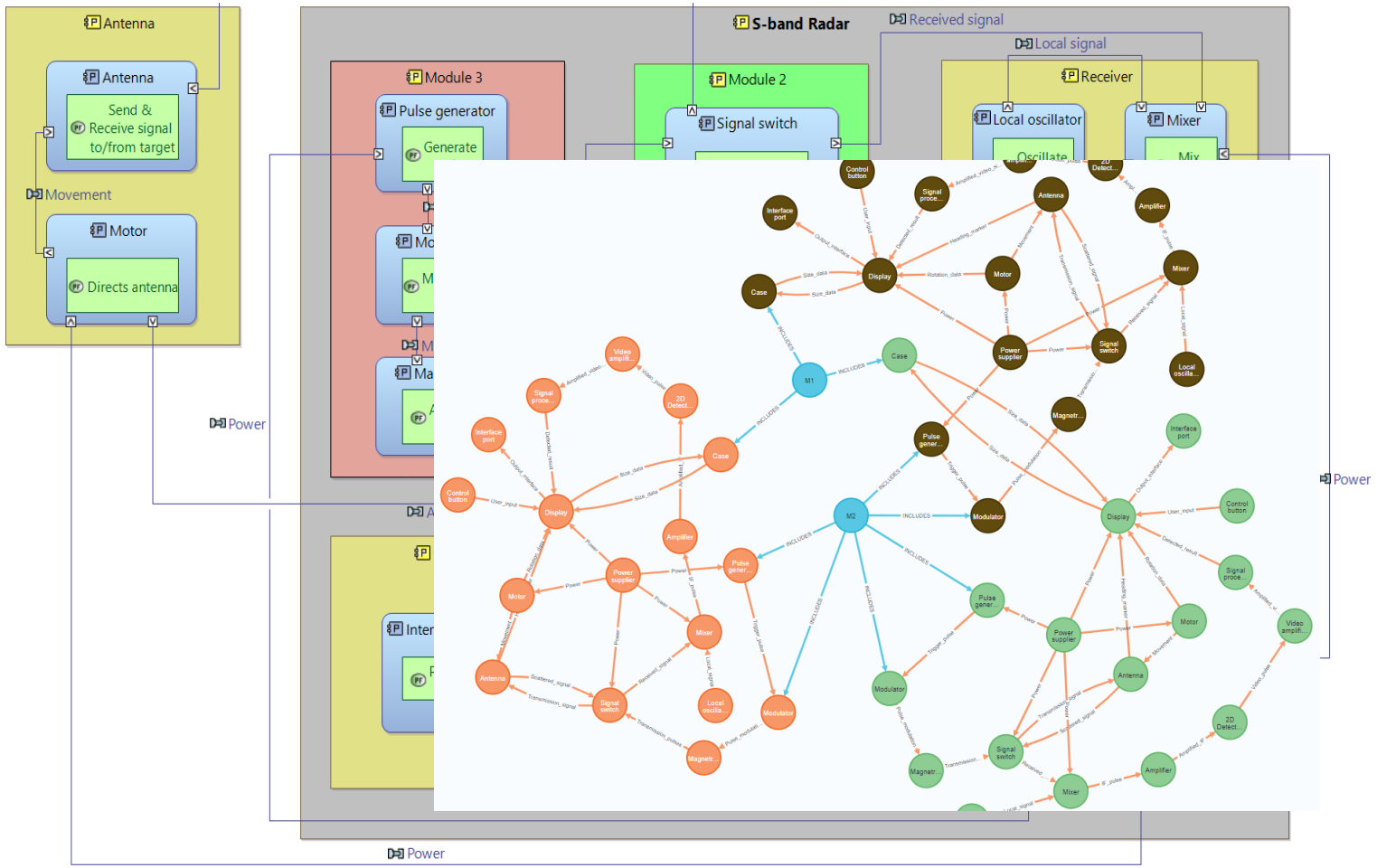


Modules	Component	Module Variation
Module 1	Control button, Display	1
Module 2	Signal switch	1
Module 3	Pulse generator, Modulator, Magnetron	28/24



Optimal design for S-band radar

Best modular design for S-band radar:



Modules	Component	Module Variation
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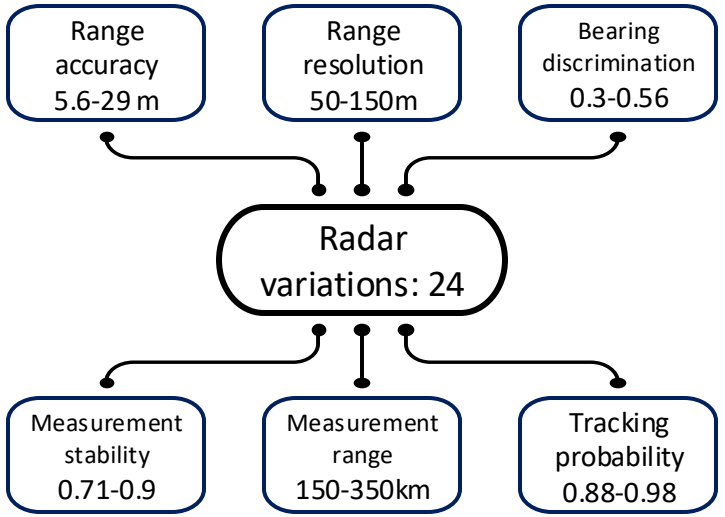
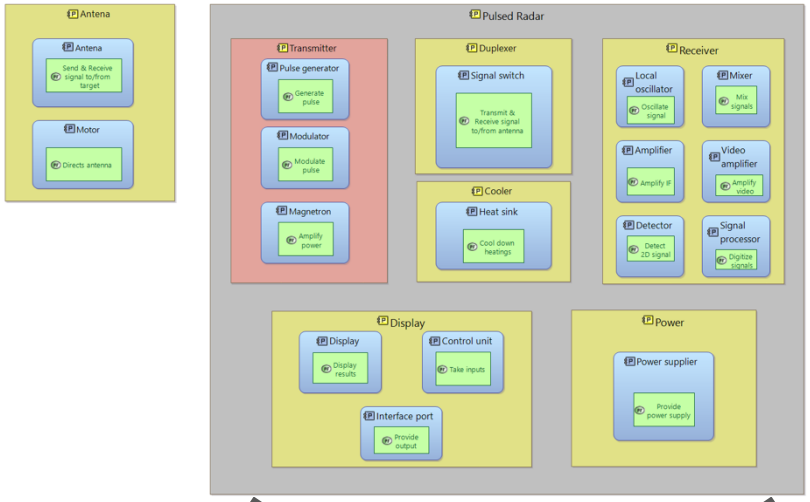
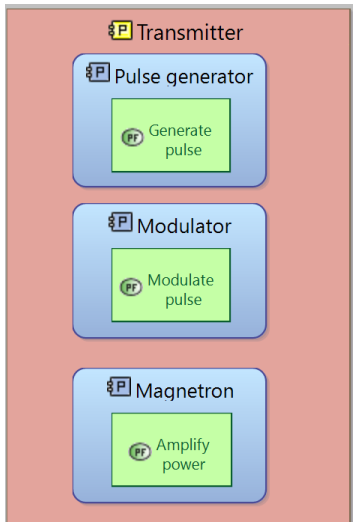
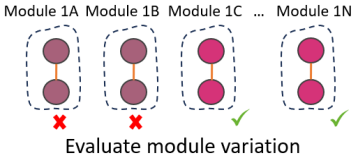


Main output

Pulsed radar



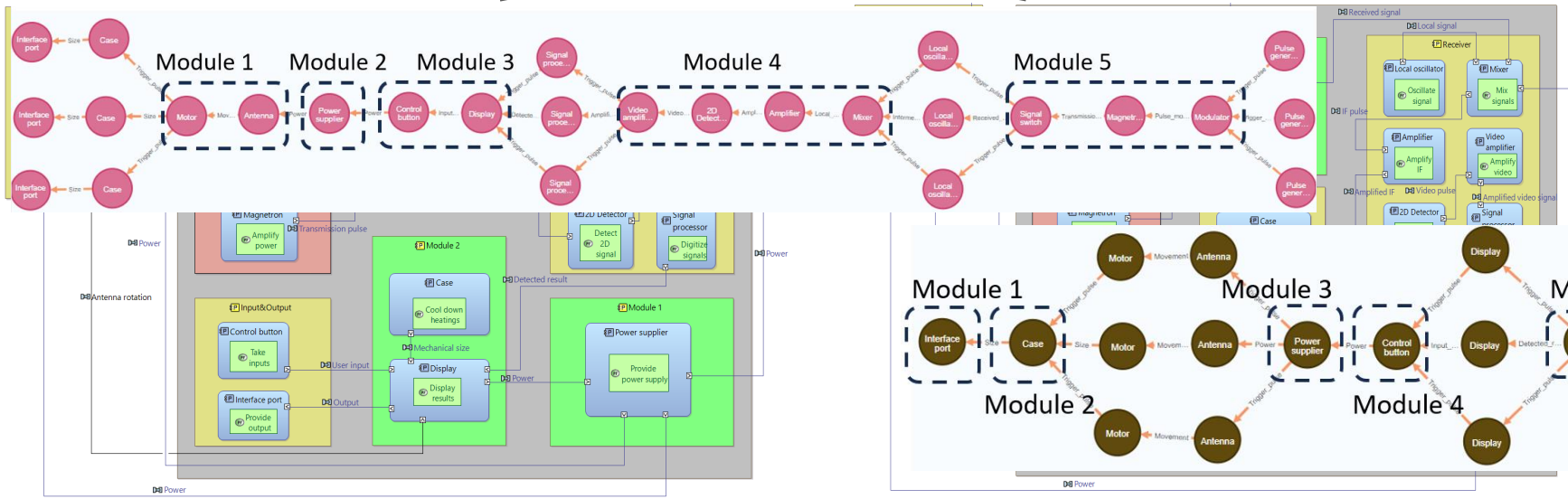




This is the important part of pulsed radar in terms modularity.

- Customization
- Complexity

X-band radar: Modular design

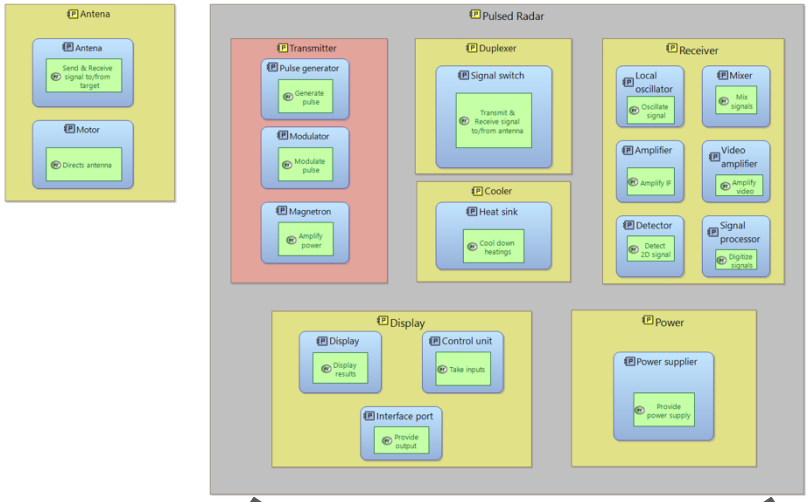


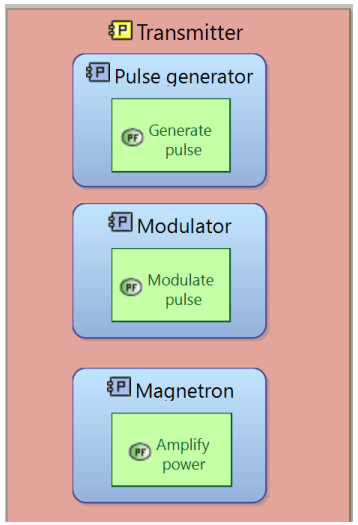
S-band radar: Modular design

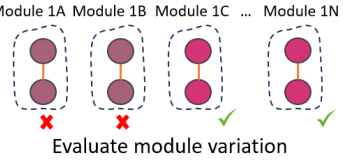
Modular designs are very similar to the real-life designs of pulsed radar system. It indicates both X- [illegible] modular higher

Decomposition | Integration | Evaluation: Extract best design on each radar

Main output



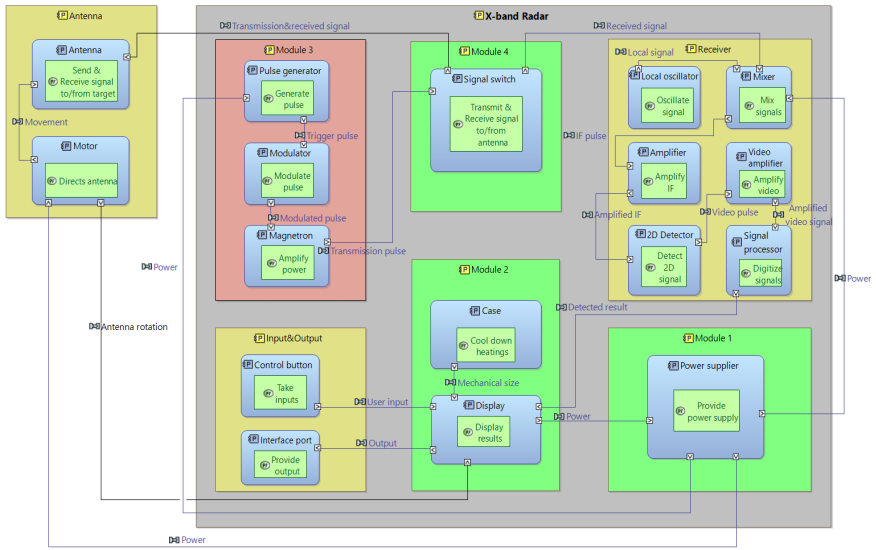




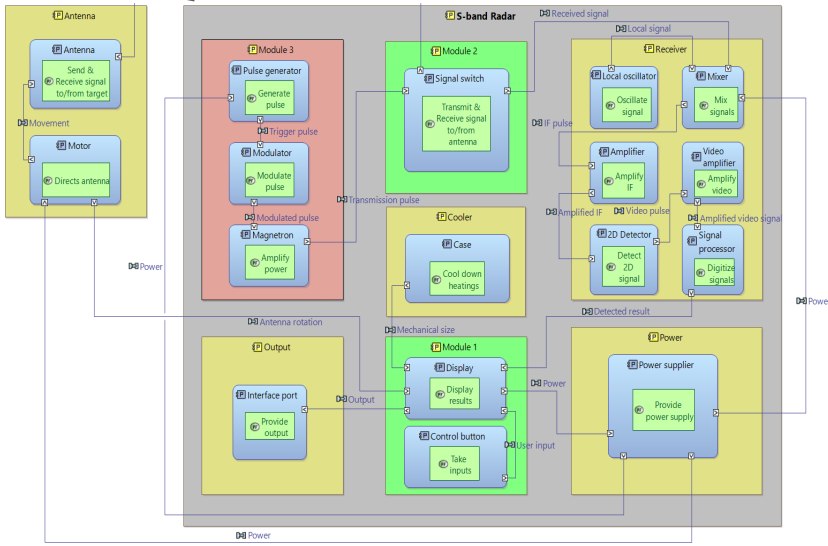
This is the important part of pulsed radar in terms modularity.

- Customization
- Complexity

X-band radar: Modular design



S-band radar: Modular design



Modular designs are very similar to the real-life designs of pulsed radar system. It indicates both X-band and S-band modular designs need that higher cost of redesigning.

Contents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Main Approach
Step 1: Decomposition
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Conclusion

Conclusion

Achievement of this study:

- The modularity of pulsed radar was challenging due to the system characteristics and need for detailed technical specifications. The data collection phase was particularly time-consuming.
- Modular designs for X-band and S-band radars were proposed, showing that customization was improved, complexity was reduced, and modularization was proven worthwhile for pulsed radar systems.
- This approach can also be applied to more complex products as the defined indices can capture intricate relationships between the units.

Conclusion

Limitations:

- In this research, input data is crucial for the modularization process, requiring extensive data from the user. If this approach is to be applied to other products, such as radar systems, detailed parameters and performance metrics should be provided.

Future prospect:

- This research focused on the physical modularization of radar systems. Future work should also address the modularization of software or logical parts.
- Trying this method with a larger number of product families would be more effective and engaging.

東京大学
THE UNIVERSITY OF TOKYO

Thank you for the attention !