



mmCESim

<https://mmcesim.org>

MMCESIM DOCUMENTATION & TUTORIALS

TASK-ORIENTED MMWAVE CHANNEL ESTIMATION SIMULATION

Version 0.1.1

WUQIONG ZHAO (TEDDY VAN JERRY)

January 11, 2023

The application ‘mmCEsim’ and this document (MMCESIM DOCUMENTATION & TUTORIALS) are open source and distributed by an MIT License.

MIT License

Copyright © 2022 – 2023 Wuqiong Zhao (Teddy van Jerry)

Permission is hereby granted, free of charge, to any person obtaining a copy of this software and associated documentation files (the “Software”), to deal in the Software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Software, and to permit persons to whom the Software is furnished to do so, subject to the following conditions:

The above copyright notice and this permission notice shall be included in all copies or substantial portions of the Software.

THE SOFTWARE IS PROVIDED “AS IS”, WITHOUT WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.

The latest edition of this document (MMCESIM DOCUMENTATION & TUTORIALS) can be freely accessed online at <https://pub.mmcesim.org/mmCESim-doc.pdf>.

Edition 2023/01/11 (corresponding to mmCEsim version 0.1.1).

mmCEsim Website: <https://mmcesim.org>

Source of This Document: <https://github.com/mmcesim/mmcesim-doc>

Contents

Preface	iii
List of Figures	v
List of Tables	vii

I PRELIMINARY

1	Preview	3
1.1	Introduction	3
1.2	Features	3
1.3	Algorithm Background	4
1.4	Software Implementation	4
2	Installation	5
2.1	Download Binary	5
2.2	Build from Source	5
2.3	Troubleshooting	6

II DOCUMENTATION

3	CLI Application	9
4	GUI Application	11
5	Web Application	13
6	ALG Language	15
6.1	Data Type	15
6.2	Function	17

6.3	Calculation (CALC)	20
6.4	Macro	20
6.5	ALG Library	20

III TUTORIALS

7	Millimeter Wave Channel Estimation	23
8	CLI Application Tutorials	25
9	GUI Application Tutorials	27
10	Web Application Tutorials	29
11	VS Code Extension Tutorials	31

Appendix

A	Additional Resources	35
A.1	Publications	35
A.2	Websites	35
B	Change History	37
	Bibliography	39
	Index	41

Preface

mmCEsim documentation & tutorials are under development!

I would like to thank Jinwen Xu for designing the elegant L^AT_EX template beaulivre, which empowers this document.

WUQIONG ZHAO
Nanjing, China
January 2023

List of Figures

1.1	mmCEsim banner.	3
5.1	Web app interface.	13

List of Tables

6.1	ALG variable basic type prefix.	15
6.2	ALG variable alias prefix.	16
6.3	ALG variable dimension.	16
6.4	ALG variable suffix.	16
A.1	Websites for users.	35
A.2	Websites for developers.	35

I

PRELIMINARY

Make preparations before we start.

Preview | 1

Before diving into documentation details, let's first have a preview of mmCEsim. Maybe you are not sure whether your research or study need this powerful tool, then read this chapter to have a glimpse of mmCEsim.

1.1 Introduction

The application is dedicated to simulate millimeter wave (mmWave) channel estimation:

$$\text{mmCEsim} = \text{mmWave} + \text{Channel Estimation} + \text{simulation},$$

where reconfigurable intelligent surface (RIS), also known as intelligent reflecting surface (IRS) [1] is supported for multiple input multiple output (MIMO) systems.



Figure 1.1: mmCEsim banner.

We offer a task-oriented simulation software for researchers to focus on algorithms only without being bothered by coding.

1.2 Features

Here is a list of basic features of mmCEsim:

- Task-oriented mmWave channel estimation formulation;
- Customizable system model;
- Extendable algorithms with our designed ALG language;
- Multiple RISs support;
- Automatic report generation (in plain text and \LaTeX PDF);
- Well-written documentation with examples and tutorials.

1.3 Algorithm Background

The task-oriented channel estimation for (RIS-assisted) mmWave MIMO systems is implemented with compressed sensing (CS), which exploits the sparsity of mmWave channels.

1.4 Software Implementation

Based on the algorithm background, we implement this software with command line interface (CLI), graphic user interface (GUI), web application and a VS Code extension.

Installation | 2

2.1 Download Binary

You can download the built binary of mmCESim from [GitHub releases](#). The built CLI binaries include support for Linux (x86), macOS (x64 and arm) and Windows (x86).

They all statically link to libraries, so theoretically no dependency is needed.

NOTE

Since GitHub Actions currently only provide x86_64 machines, the binary for macOS with arm architecture is built manually on my MacBook Air with an M1 chip.

2.2 Build from Source

Since mmCESim is built with CMake, so you can easily build the source on Unix-based systems. For Windows, I think there are similar ways.

On a Unix-based system, you can simply use the following code to build and install mmCESim.

```
1 git clone https://github.com/mmcesim/mmcesim.git --recurse-submodules
2 cd mmcesim
3 cmake . build
4 cd build
5 make
6 sudo make install
```



The option `--recurse-submodules` is required because some dependencies of mmCESim Are managed by Git sub-modules.

You need to have a C++ compiler that supports C++17 standard, and have installed the Boost library (statically) of minimum version 1.70.0 on your system. You can install them easily on Unix-based systems with your favourite package manager. For Windows users, please follow the official instruction of Boost.

```
1 # Debian, Ubuntu
2 sudo apt install libboost-dev
3 # Arch
4 sudo pacman -Ss boost
5 # macOS
6 sudo port install boost # with MacPorts
7 brew install boost      # with HomeBrew
```

If you want to build the GUI app as well, you need to install Qt6.

Some options can be configured when calling `cmake`.

- `CMAKE_BUILD_TYPE`: Build type (default as `Release`)
- `CMAKE_INSTALL_PREFIX`: Installation prefix (default as system path)
- `MMCESIM_BUILD_ASTYLE`: Build `astyle` Code Formatter (default as `ON`)
- `MMCESIM_BUILD_GUI`: Build mmCEsim GUI App with Qt (default as `OFF`)
- `MMCESIM_APPLE_COPY_SH`: Copy additional shell script for macOS (default as `OFF`).

For example, you may use `cmake . build -D CMAKE_INSTALL_PREFIX=usr/mmc esim` to install mmCEsim to the directory `usr/mmc esim`.

2.3 Troubleshooting

2.3.1 macOS Safety Warning

You may view a safety warning after downloading the binary from GitHub Releases. The `trust_mmc esim.sh` is a script to remove that warning. (Give the script proper permission before running in its directory). Technically, it does `xattr -r -d com.apple.quarantine <binary>`.



DOCUMENTATION

Every syntax and option in details.

CLI Application | 3

GUI Application | 4

Web Application | 5

The example web app page is shown in Fig. 5.1.

The screenshot displays a web browser window with the address bar showing `app.mmcesim.org`. The page title is "mmCESim Web App" with a subtitle "Task-oriented Millimeter Wave Channel Estimation Simulation". Navigation links for "About", "Website", "GitHub", and "v0.0.1" are in the top right. A light blue notification bar at the top states: "The web app is currently under development." Below this is a horizontal menu with icons and labels for "Project", "System", "Channels", "Estimation", "Simulation", and "Report". The "Project" tab is active. The form includes three main sections: "Project Name" with a text input field containing the placeholder "Project name (also output file name)"; "Author Name (Optional)" with a text input field containing the placeholder "Author name"; and "Descriptions (Optional)" with a large text area containing the placeholder "You may describe your project here." At the bottom right of the form are three buttons: "Cancel", "Generate" (highlighted in green), and "Save Config". A footer at the very bottom reads: "Developed, designed and hosted by Wuqiong Zhao. © 2022 Wuqiong Zhao (Teddy van Jerry), Southeast University".

Figure 5.1: Web app interface.

ALG Language

6

6.1 Data Type

6.1.1 Why Need Data Type

Languages Python and Matlab/Octave are weakly typed which can be convenient for writing the code. However, that is problematic for implementation. The efficiency is not satisfactory compared to C++, and sometimes you may encounter ambiguous error information in Matlab. Therefore, for the sake of efficiency and generality, ALG language is designed to be **strongly typed**.

6.1.2 Structure

The type specification is very simple, because ALG language concentrates on matrices. Basically, the structure of ALG language is

prefix + dimension + suffix.

For example, f2c means a matrix (dimension is 2) with data type as float and property as a constant.

6.1.3 Specifiers

6.1.3.1 Prefix

Basic Type Prefix Basic type just names the element type. They are shown in Table 6.1.

Table 6.1: ALG variable basic type prefix.

Prefix	Type	C++ Type	Python Type	MATLAB/Octave Type
c	Complex	<code>cx_double</code>	<code>complex</code>	<code>complex</code>
f	Float	<code>double</code>	<code>double</code>	<code>double</code>
i	Integer	<code>int</code>	<code>int</code>	<code>int64</code>
u	Unsigned Integer	<code>uword</code>	<code>uint</code>	<code>uint64</code>
b	Boolean	<code>bool</code>	<code>bool</code>	<code>logical</code>
s	String	<code>std::string</code>	<code>str</code>	<code>string</code>
h	Character	<code>char</code>	<code>char</code>	<code>char</code>

Table 6.2: ALG variable alias prefix.

Alias Prefix	Type	Equivalent Two-character Type
v	(Column) Vector	c1
r	Row Vector	c2
m	Matrix	c2
t	Tensor	c3
d	Double	f0

Alias Prefix Alias prefixes not only set the element type, but also the dimension. They are the one character alias for a two-character type. A list of alias prefixes is shown in Table 6.2.

! v, r, m and t are all for **complex** types. For a non-complex type, you need to use the normal two-character way.
 ! Row vector (r) is actually regarded as a matrix for simplicity, so its dimension is still 2. Only column vector (c) is the real vector. But there can be differences in terms of **INIT**, so it should not be confused with m.

6.1.3.2 Dimension

Dimensions range from 0 to 3. Details are shown in Table 6.3.

Table 6.3: ALG variable dimension.

Dimension	Type	C++ Type
0	Scalar	—
1	Vector	Col
2	Matrix	Mat
3	Tensor	Cube

! Dimension for a scalar can not be omitted.

Please note that matrices are stored in **column major** order, which is the default order in C++ (Armadillo) and Matlab/Octave. In Python (NumPy), it is equivalent to the option `order='F'`.

! You should always remember the column **major order**, especially if you use are accustomed to Python.
 ! The order will make a big difference to matrix reshape and vectorization.

6.1.3.3 Suffix

All suffixes of ALG variables are shown in Table 6.4.

Table 6.4: ALG variable suffix.

Suffix	Meaning	C++	Python	MATLAB/Octave
c	Constant	<code>const</code>	(None)	<code>persistent</code>
r	Reference	<code>reference</code>	(None)	(None)

TIP

Two suffixes cannot be used together and there is also no need to do so. The use of `r` is mainly in function, allowing a parameter to be changed inside the function body.

6.2 Function

6.2.1 Syntax Basics

The initiative of proposing a new programming language for algorithm implementation is based on the multi-backend design of mmCEsim. The language is specially designed so that it can be exported to C++ (with Armadillo), Python (with NumPy) and MATLAB/Octave easily.

Every line of ALG language calls a function. Let's first have a look at its basic structure before we cover its details.

```
1 ret1::type1 ret2 = FUNC param1 param2::type2 key1=value1 key2=value2::type3 # com.
```

It may look like an assembly language at the first glance, due to all parameters are separated by space. But it is actually much more convenient. Here are some basic rules:

- All tokens are separated by space.
- Function names are in all upper cases, like `CALC`, `WHILE`.
- Indentation does not matter. Blocks are ended with `END`.
- The function line is mainly composed of three parts: **return values**, **function name**, **parameters**, in the left to right direction.
- Some functions may not have return values, and you may also omit the return values. If there are return values, there is a `=` between return values and function names.
- Function name is the first word on the right of `=` (if there are return values) or the first word of line (if there is no return value).
- Like Python, parameters can be passed in by two ways:
 - 1) **value in position**: Like `param1` and `param2` in the above example. Parameters in different positions correspond to different usages in the function. This is the only way in C++.
 - 2) **key and value**: Parameters can also be specified using key and its corresponding value. `value1` and `value2` are passed in using this method. It should be noted that there should be no space around the `=` between key and value.

There are some special cases that parameters are viewed as a whole, for example `COMMENT` and `CALC`.

- If a parameter contains space or special characters, you need to use the double quotes like "param with space" and escape special characters as in C++ and Python.
- You may optionally specify the type of return value and parameters with `::` after the value. For example, in the above example `dtype1`, `dtype2` and `dtype3` are type specifications for `ret1`, `param2` and `value2`, respectively. For more information about data type, please refer to [data type of ALG language](#).
- Like Python, the backslash (`\`) at the end of the line can be used for continuing the function on next line.
- Comments start with the hash (`#`) like Python.

! There should be no space around the `=` between key and value for parameters. For example, `key=val` is valid while `key = val` is forbidden.

Special rules may be applied for different functions. Please refer to the specific documentation for each function.

6.2.2 BRANCH

Declare start of the scope of job algorithms.

Explanations

This is useful in estimation. Contents between [BRANCH](#) and [MERGE](#) will be repeated for different algorithms. So you need to place compressed sensing estimation [ESTIMATE](#) and [RECOVER](#) inside.

Example

[Example of OFDM OMP.](#)

6.2.3 BREAK

Break from a block (for [FOR](#), [FOREVER](#), [LOOP](#), [WHILE](#)).

Explanations

The same as break in C++, Python and MATLAB/Octave. This function takes no parameter.

Example

Example with [FOREVER](#).

6.2.4 CALC

Make arithmetic calculations.

Explanations

There are two kinds of CALC usage: **inline** and **standalone**:

- **inline**: The contents to be calculated are placed in a set of dollar signs, like \LaTeX syntax: $\$some\ operations \rightarrow to\ be\ calculated\$$.
- **Standalone**: This is like a normal function, with function name as [CALC](#). You may also omit the function name [CALC](#) since it is the default function name if nothing is specified. Therefore, $result = \text{CALC your expression}$ is equivalent to $result = \text{your expression}$.

For more information about the [CALC](#) syntax, please refer to §6.3.

! For safety, you should not use anything other than ANSI characters in [CALC](#) functions. Otherwise, there can be undefined behaviour.

If you want the calculation result to be a new variable, you may use function [NEW](#).

Example

EXAMPLE 6.1 (Example of CALC)

```
1 a = CALC b + 2 # explicit CALC function
2 a = \sin(b) @ c # implicit CALC function
3 a = b^H + c^{-1} # conjugate transpose and inverse
4 c = b_{2, 3} # get element of a matrix
5 c = \abs{b_{:, 3}} + \pow(b_{}, 2) # use : in subscript & use {} for function
6 \exp2(a + c .* d) ./ e^T -f_{:,3,1:index} # element-wise operator and
   \rightarrow subscript : range
```

Equivalent C++ Code

```
1 a = b + 2;
2 a = arma::sin(b) * c;
3 a = b.t() + c.i();
```

```

4 c = b(2, 3);
5 c = arma::abs(b(arma::span::all, 3)) + arma::pow(b, 2);
6 arma::exp2(a + c % d) / e.st() - f(arma::span::all, 3, arma::span(1, index));

```

6.2.5 CALL

Call a custom function defined by **FUNCTION**.

6.2.6 COMMENT

Place a line of comment in the exported code.

Explanations

All contents after the function keyword **COMMENT** are considered as comments.

Example

EXAMPLE 6.2 (Example of COMMENT)

```
1 COMMENT Hi, this is a comment!
```

Equivalent C++ Code

```
1 // Hi, this is a comment!
```

Equivalent Python Code

```
1 # Hi, this is a comment!
```

Equivalent MATLAB/Octave Code

```
1 % Hi, this is a comment!
```

6.2.7 CPP

Write standard C++ contents.

Explanations

All contents after the **CPP** keywords are copied to exported codes. For backend other than C++, this function is ignored.

Example

EXAMPLE 6.3 (Example of CPP)

```
1 CPP std::cout << "Standard C++ Language!" << std::endl;
```

Equivalent C++ Code

```
1 std::cout << "Standard C++ Language!" << std::endl;
```

For Python, MATLAB/Octave, nothing will happen with the **CPP** function.

6.2.8 ELSE

Used in **IF** blocks.

Explanations

This function implements as `else` in C++, Python and MATLAB/Octave. There is no parameter for the `ELSE` function.

Example

Example with `IF`.

6.2.9 END

End of a block for `ELSE`, `ELIF`, `FUNC`, `FOREVER`, `IF`, `LOOP`, `WHILE`.

Explanations

In C++, this functions as `}`, in Python it is the indentation goes back for one block. In MATLAB/Octave, it is the `end` specification.

Example

Example with `FOR`, `FOREVER`, `IF`, `LOOP`, `WHILE`.

6.2.10 ESTIMATE

`CALL standard ALG functions` to estimate the sparse channel with compressed sensing (CS).

6.2.11 FUNCTION

Start a function definition.

Explanations

The function requires an `END` to mark the end of the function.

6.2.12 IF

Conditional statement.

6.3 Calculation (CALC)

6.4 Macro

6.5 ALG Library

III

TUTORIALS

Step-by-step guide on using mmCEsim.

Millimeter Wave Channel Estimation



Millimeter wave channel estimation for multiple input multiple output (MIMO) systems techniques are discussed in [2].

CLI Application Tutorials



GUI Application Tutorials



Web Application Tutorials | 10

VS Code Extension Tutorials

11



APPENDIX

Additional information about mmCEsim.

Additional Resources



A.1 Publications

A brief introduction of mmCEsim is given in the [poster](#) at the 2022 National Postdoc Seminar in Nanjing, which I attend as the only undergraduate student, and got the Honorable Mention award.

This document is also published online at <https://pub.mmcesim.org/mmCEsim-doc.pdf>.

A.2 Websites

A.2.1 For Users

If you are the user of mmCEsim and wants to know more, you may find the following websites in Table A.1 useful.

Table A.1: Websites for users.

Website	URL
Homepage	https://mmcesim.org
Web Application	https://app.mmcesim.org
Blog	https://blog.mmcesim.org
Publications	https://pub.mmcesim.org
VS Code Extension	https://marketplace.visualstudio.com/items?itemName=mmcesim.mmcesim

A.2.2 For Developers

If you are a developer and maybe want to contribute to the mmCEsim project, you can find additional websites in Table A.2.

Table A.2: Websites for developers.

Website	URL
GitHub Organization	https://github.com/mmcesim
C++ Dev Documentation	https://dev.mmcesim.org
CLI App Wiki	https://github.com/mmcesim/mmcesim/wiki

Change History



B.1 v0.1.1 2023/01/11

New Features

- Multi RIS assisted systems support ([#3](#));
- RIS pattern design support ([#17](#)).

Bug Fixes

- Fix cmake install configurations.

News

- Automated release process with a better CI workflow ([#20](#)).

B.2 v0.1.0 2022/10/16

New Features

- Basic mmWave MIMO systems channel estimation support;
- Design of ALG language;
- Export of code with Armadillo library;
- Auto simulation ([#5](#)).

B.3 v0.0.1 2022/07/27

Though the app has not been fully developed, the task-oriented concept has already been established.

Bibliography

- [1] Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network", *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 106–112, Jan. 2020.
- [2] J. Lee, G.-T. Gil, and Y. H. Lee, "Channel estimation via orthogonal matching pursuit for hybrid MIMO systems in millimeter wave communications", *IEEE Trans. Commun.*, vol. 64, no. 6, pp. 2370–2386, Jun. 2016.

Index

Symbols

#	17
\	17

A

ALG library	20
-------------	----

B

b	15
BRANCH	18
BREAK	18

C

c	15, 16
CALC	20
CALC	18
calculation	20
CALL	19
COMMENT	19
CPP	19

D

d	16
data type	15
dimension	16

E

ELSE	19
------	----

END	20
ESTIMATE	20

F

f	15
FUNCTION	20
function	17

H

h	15
---	----

I

i	15
IF	20

M

m	16
macro	20

P

prefix	15
alias	16
b	15
basic type	15
c	15
d	16
f	15
h	15
i	15
m	16

r	16
s	15
t	16
u	15
v	16

R

r	16
---	----

S

s	15
specifier	15
suffix	16
c	16

r	16
---	----

T

t	16
---	----

U

u	15
---	----

V

v	16
---	----