Software Requirements Specification for Radio Signal Strength Calculator

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Revision History

Date	Version	Notes
Oct 5	1.0	First draft of the document
Oct 29	1.1	Revision 1 of the document

1 Reference Material

This section records information for easy reference.

1.1 Table of Units

Throughout this document SI (Système International d'Unités) is employed as the unit system. In addition to the basic units, several derived units are used as described below. For each unit, the symbol is given followed by a description of the unit and the SI name.

symbol	unit	SI
m	length	metre
$\mathrm{m\,s^{-1}}$	speed	metre per second
Hz	frequency	hertz
dBm	power	decibel-milliwatt
rad	phase angle	radian
W	power	watt ($\mathrm{W = J\,s^{-1}}$)

1.2 Table of Symbols

The table that follows summarizes the symbols used in this document along with their units. The choice of symbols was made to be mostly consistent with the radio frequency literature and with existing documentation for radio wave propagation models.

symbol	unit	description
(x, y)	m	Cartesian Position Coordinates in a 2- dimensional space
$d_{\mathrm{a,b}}$	m	Euclidean Distance between point a and point b in a 2-D space
Δd	m	Difference between two travelling paths of a radio signal
λ	m	Signal wavelength
tsm	$-$	Transmitter
Pos_{tsm}	m	2-D position of the transmitter
G_{tsm}	dB	Directional gain of the transmitter's antenna
sp	$-$	Sampling point
Pos_{sp}	m	2-D position of the sampling point
G_{sp}	dB	Directional gain of the antenna on the receiver located at the sampling point
p	m	A point
p'	m	Mirror point of point p

t	m	A randomly picked point on the reflection plane
t'	m	The point where the line passing the point p and its mirror point p' intersects the reflection plane
$Ind_{r,x}$	$-$	A boolean indicating whether the reflected signal's path is valid or not
$Ind_{t,x}$	$-$	A boolean indicating whether the segment of the signal's path intersects wall x or not
D_t	dB	Directional gain of the transmitter's antenna
D_r	dB	Directional gain of the receiver's antenna
n	$-$	Unit normal vector of a plane
i	$-$	Imaginary unit
n_x	$-$	Unit normal vector of wall x
C_x, D_x	m	Starting and ending vertices of wall x in the 2-D space
x_{C_x}, x_{D_x}	m	x-Coordinates of vertices C_x and D_x
y_{C_x}, y_{D_x}	m	y-Coordinates of vertices C_x and D_x
E, F	m	Starting and ending vertices of a signal path in the 2-D space
x_E, x_F	m	x-Coordinates of vertices E and F
y_E, y_F	m	y-Coordinates of vertices E and F
M	$-$	Coefficient matrix of a line's equation in 2-D space
$m1, m2$	$-$	Components in in matrix M
k	m	Coefficient of a line's equation in 2-D space
$\overline{C_x D_x}$	m	The line segment representing wall x in the 2-D space
N_w	$-$	Total number of walls
N_r	$-$	Total number of first-order reflected signals
P^{dBm}	dBm	Power in dBm
P_{tsm}	W	Power level of the transmitter
P_{tsm}^{dBm}	dBm	Power level of the transmitter in dBm
P_{sp}	W	Received signal strength
P_{sp}^{dBm}	dBm	Received signal strength in dBm
$FSPL$	$-$	Free-space path loss of radio energy
$FSPL_{tsm\to t'}$	$-$	Free-space path loss of energy of the radio signal travelling from the transmitter to the point t'
R	$-$	Wall reflectance
T	$-$	Wall transmittance
R_x	$-$	Reflectance of wall x
T_x	$-$	Transmittance of wall x

$L^i_{e,\Omega}$	W	Spectral radiance received by surface Ω
$L^t_{e,\Omega}$	W	Spectral radiance passed through surface Ω
$L^r_{e,\Omega}$	W	Spectral radiance reflected by surface Ω
c	m/s	Speed of light
f	Hz	Signal frequency
HP	$-$	A hyperplane in a Euclidean space
ϕ	rad	Phase angle of a wave
$\Delta\phi$	rad	Phase difference between two waves
ϕ_{sum}	rad	Phase angle of the combined wave
ϕ_{FORS}	rad	Phase angle of the first-order reflected signal
ϕ_{sp}	rad	Phase angle of received signal at the sampling point
A	$-$	Amplitude of a sinusoidal wave
A_{sum}	$-$	Amplitude of the combined wave
A''	W	Complex power of a radio signal
x	m	The x coordinate in the Cartesian coordinate system
y	m	The y coordinate in the Cartesian coordinate system
LOS	$-$	Line-of-sight signal
$FORS$	$-$	First-order reflected signal
$RS1$	$-$	Pre-reflection signal
$RS2$	$-$	Post-reflection signal
P_{LOS}	W	Power of Line-of-sight signal
P_{FORS}	W	Power of First-order reflected signal
P_{RS1}	W	Power of Pre-reflection signal
P_{RS2}	W	Power of Post-reflection signal

1.3 Abbreviations and Acronyms

symbol	description
A	Assumption
DD	Data Definition
GD	General Definition
GS	Goal Statement
IM	Instance Model
LC	Likely Change
PS	Physical System Description
R	Requirement
SRS	Software Requirements Specification
RSSC	Radio Signal Strength Calculator for indoor wireless communication systems
T	Theoretical Model
2-D	2-Dimensional

2 Introduction

From the evaluation of Wi-Fi signal coverage to indoor localization, radio signal strength is an essential information in various application scenarios of indoor wireless communication systems. However, collecting signal strength data in the real world is both expensive and time-consuming. We intend to develop a tool to simulate the indoor transmission of a radio signal and obtain the signal's strength, hence avoiding expensive on-field surveys.

The following section provides an overview of the Software Requirements Specification (SRS) for Radio signal Strength Calculator for indoor wireless communication systems (RSSC). This section explains the purpose of this document, the scope of the requirements, the characteristics of intended readers, and the organization of the document.

2.1 Purpose of Document

The essential purpose of this document is to clarify the purpose and requirements for RSSC. This document also specifies the assumptions, theoretical models, science definitions and other model derivation information to help the reader understand and verify the purpose and scientific basis of RSSC.

2.2 Scope of Requirements

The scope of requirements includes analysis of the radio signal transmission in a 2 - Dimensional space inside a room.

2.3 Characteristics of Intended Reader

Intended readers are supposed to have a technical background in radio frequency engineering. They should be familiar with telecommunication systems; they should understand basic concepts in electromagnetism and optics (covered by undergraduate level 1 engineering physics); they should understand undergraduate level 2 engineering mathematics.

2.4 Organization of Document

This document follows the standard pattern of presenting goals, assumptions, theories, and definitions. For readers that would like a more bottom up approach, they can start reading the instance models in 4.2.5 and trace back to find any additional information they require.

The goal statement (4.1.3) is refined to the theoretical models(4.2.2) and further, to the instance models (subsubsection 4.2.5), with definitions of data (4.2.4) needed to construct instance models. The instance models provide the set of algebraic equations that must be solved.

3 General System Description

This section provides general information about the system. It identifies the interfaces between the system and its environment, describes the user characteristics and lists the system constraints.

3.1 System Context

The system context is shown in Figure 1: RSSC takes inputs from the user and handle all the calculations within itself, then provides outputs to the user. The arrows show the data flow between RSSC and the environment.

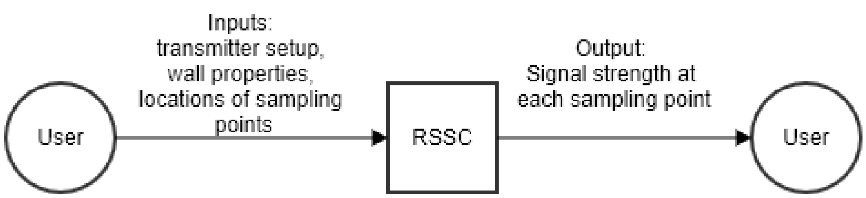

Figure 1: System Context

- User Responsibilities:
  - Provide correct inputs including transmitter settings, wall properties, and sampling locations to RSSC
  - Ensure the software assumptions satisfy the problem that the user wants to solve
- RSSC Responsibilities:
  - Detect data type mismatch, such as a string of characters instead of a floating point number
  - Determine if the input data satisfy the system's constraints for input data or not
  - Calculate signal strength at each sampling point provided by the user

3.2 User Characteristics

The end user of RSSC should have an understanding of undergraduate Level 1 physics; should know what is a Cartesian coordinate system, and should be able to read floor map of a building.

3.3 System Constraints

There are no system constraints.

4 Specific System Description

This section first presents the problem description, which gives a high-level view of the problem to be solved; then provides the solution's characteristic specification, including the assumptions, theories, definitions and the instance models.

4.1 Problem Description

RSSC is intended to simulate transmission of a radio signal in a room, and predict the received signal strength at any location in that room where the user wants to measure.

4.1.1 Terminology and Definitions

This subsection provides a list of terms that are used in the subsequent sections and their meaning, with the purpose of reducing ambiguity and making it easier to correctly understand the requirements:

- Radio signal: Also known as radio wave, a type of electromagnetic radiation with a frequency range from 30Hz to 300GHz. In wireless communication systems, radio signals are a medium to transmit information between devices.
- Transmitter: Source of any radio signals. A transmitter is an electronic device that sends a radio signal by injecting a current into its antenna.
- Power level of the transmitter: Power of the current fed into the transmitter's antenna.
- Receiver: An electronic device that receives radio signals from transmitters. A radio signal generates an electric current in a receiver through the receiver's antenna.
- Received signal strength: Power of the current that the radio signal from a given transmitter generates in the given receiver.
- Antenna: A circuit to transfer radio signals into electric current or vise versa.
- Isotropic Antenna: A type of antenna whose sending efficiency and receiving sensitivity are not affected by its orientation.
- Sampling Point: The position where a measurement is taken. In RSSC, sampling points are where the user wants to locate the simulated receivers and find the received signal strengths.

- Line of sight signal: The radio signal that travels in a straight line from the transmitter to the receiver.
- k^{th}-order reflected signal: The radio signal that takes k times of reflection travelling from the transmitter to the receiver.

4.1.2 Physical System Description

The physical system of RSSC, as shown in Figure 2, includes the following elements:

PS1: All walls of a room, but not including floor and ceiling.

PS2: One transmitter.

PS3: One or more receivers.

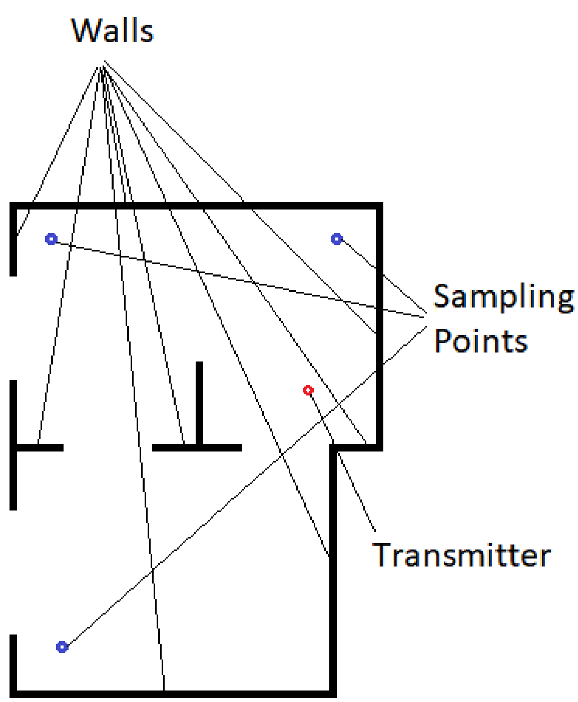

Figure 2: Example Floor Map

4.1.3 Goal Statements

Given the location and power level of the transmitter, the frequency of the transmitting signal, a list of all walls of a room with their dimensions, locations, transmittance, and reflectance, and a list of sampling points with their locations, the goal statement is:

GS1: Calculate the received signal strength in dBm at each sampling point.

4.2 Solution Characteristics Specification

The instance models that govern RSSC are presented in Subsection 4.2.5. The information to understand the meaning of the instance models and their derivation is also presented, so that the instance models can be verified.

4.2.1 Assumptions

This section simplifies the original problem and helps in developing the theoretical model by filling in the missing information for the physical system. The numbers given in the square brackets refer to the theoretical model [T], general definition [GD], data definition [DD], instance model [IM], or likely change [LC], in which the respective assumption is used.

A1: The space to simulate radio signal transmission is a 2-dimensional space parallel to the room's floor. (Ref. By T1, DD3, IM3, IM1, IM2, IM4, IM5)

A2: there are no reflections from the ceiling or the floor. (Ref. By IM7, IM8, IM9)

A3: Radio signals do not have diffuse reflections. (Ref. By DD1, T2, IM7, IM9)

A4: Transmitters have isotropic antennas (received signal strength is independent to the orientation of the transmitter). (Ref. By GD3)

A5: Receivers have isotropic antennas (received signal strength is independent to the orientation of the receiver). (Ref. By GD3)

A6: Walls have no thickness. (Ref. By DD2, GD2)

A7: Walls are planar. (Ref. By DD1, T2, T3, T1, , T4, T5)

A8: Walls have positive lengths. (Ref. By IM1, IM2, IM3, IM4, , T5)

A9: 2^{nd}-or-higher-order reflected signals are negligible. (Ref. By IM9)

A10: Only one transmitter appears in each analysis/simulation case. (Ref. By GD1, IM9))

A11: Waveform for all radio signals are sinusoidal. (Ref. By IM8, GD1)A

4.2.2 Theoretical Models

This section focuses on the general equations and laws that RSSC is based on.

Number	T1
Label	**Euclidean Distance in 2-D Space**
Equation	$d_{\mathrm{a,b}} = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2}$ for $(x, y)_a = (x_a, y_a)$ and $(x, y)_b = (x_b, y_b)$
Description	The above equation gives the Euclidean distance between point a and point b as a function of Cartesian position coordinates of point a and point b.
Source	Wikipedia (2020b)
Ref. By	GD2, GD3, IM8, IM4

Number	T2
Label	**Image Source Model**
Equation	$p' = p - 2n(n \cdot (p - t))$
Description	The spectral reflection of a plane with unit normal vector n generates a virtual point p' for a real point p. Such p' can be found by the above equation. t is a randomly picked point on the reflection plane. In a 2-D space (according to assumption A1), the reflection plane is a line and t should be on that line.
Source	Thomas (2016)
Ref. By	IM4, IM7

Number	T3
Label	**Friis Transmission Formula**
Equation	$P_{sp} = \frac{P_{tsm} G_{tsm} G_{sp} \lambda^2}{(4\pi d_{tsm,sp})^2}$
Description	The Friis Transmission Formula is a fundamental equation in radio propagation theory. The formula illustrates the relationship between received signal strength (P_{sp}), power level of the transmitter (P_{tsm}), directional gains of transmitter' and receiver's antennas (G_{tsm} and G_{sp}), signal wavelength (λ), and distance between the transmitter and the receiver ($d_{tsm,sp}$).
Source	Anonymous (2015)
Ref. By	DD3

4.2.3 General Definitions

This section collects the laws and equations that will be used in building the instance models.

Number	GD1
Label	**Wave Superposition**
Units	W
Equation	$A_{sum} e^{i\phi_{sum}} = \sum_{n=1}^{N} A_n e^{i\phi_n}$ for N waves from n = 1 to n = N
Description	Multiple sinusoidal waves at the same point will superpose and add together as a combined wave. Here each wave is represented as a phasor with an amplitude A and a phase angle ϕ. Addition of sinusoidal waves is the same as addition of complex numbers in polar form.
Source	Wikipedia (2020e)
Ref. By	IM9

Number	GD2
Label	**Phase Difference And Path Difference Equation**
Units	rad
Equation	$\Delta\phi = \frac{2\pi\Delta d}{\lambda}$
Description	A wave have different phases when it travels over different distances. The relation between phase difference and distance difference is linear. This equation gives the phase difference of two fractions of a signal as a function against the difference between the length of the signal fractions' travelling paths.
Source	Anonymous (2020)
Ref. By	IM8

Number	GD3
Label	**Free Space Path Loss Model**
SI Units	-
Equation	$FSPL = \frac{P_{tsm}}{P_{sp}} = (\frac{4\pi d_{tsm,sp}}{\lambda})^2 = (\frac{4\pi f d_{tsm,sp}}{c})^2$
Description	The equation of free space path loss is derived from Friis Transmission Formula (T3). According to assumptions A4 and A5, directional gains of antennas are always equal to 1. The free space path loss ($FSPL$) gives the ratio of the power level of the transmitter to the received signal strength in an environment without any obstackles. A larger value of $FSPL$ indicates a higher power loss in signal propagation.
Source	Whitaker (1996)
Ref. By	IM6, IM7

Detailed derivation of simplified rate of change of temperature

4.2.4 Data Definitions

This section collects and defines all the data needed to build the instance models. The dimension of each quantity is also given.

Number	DD1
Label	**Reflectance**
Symbol	R
Units	-
Equation	$R = \frac{L^r_{e,\Omega}}{L^i_{e,\Omega}}$
Description	Reflectance of a surface is the ratio of the reflected radiance's power of a surface ($L^r_{e,\Omega}$) to the power of the radiance went into that surface ($L^i_{e,\Omega}$).
Source	Wikipedia (2020c)
Ref. By	IM7

Number	DD2
Label	**Transmittance**
Symbol	T
Units	-
Equation	$T = \frac{L^t_{e,\Omega}}{L^i_{e,\Omega}}$
Description	Reflectance of a wall is the ratio of the power of the radiance that transmitted through the wall ($L^t_{e,\Omega}$) to the power of the radiance went into that wall ($L^i_{e,\Omega}$).
Source	Wikipedia (2020d)
Ref. By	IM6,IM7

Number	DD3
Label	**Unit Normal Vector**
Symbol	n
Units	-
Equation	$n = \frac{\nabla F}{\|\|F\|\|}$
Description	The unit normal vector of a surface is a vector perpendicular to that surface and have a magnitude of 1.
Source	Weisstein (2020)
Ref. By	T2, IM3

Number	DD4
Label	**Decibel-Milliwatt**
Symbol	P^{dBm}
Units	dBm
Equation	$P^{dBm} = 30 + 10 \log_{10} \frac{P}{1\text{W}}$ $P = 1\text{W} \cdot 10^{\frac{P^{dBm}-30}{10}}$
Description	dBm is a unit to represent the magnitude of power. In RSSC, the transmitter power level in the user input and received signal strength in the output are in dBm.
Source	Wikipedia (2020a)
Ref. By	IM6, IM7

4.2.5 Instance Models

This section transforms the problem defined in Section 4.1 into one which is expressed in mathematical terms. It uses concrete symbols defined in Section 4.2.4 to replace the abstract symbols in the models identified in Sections 4.2.2 and 4.2.3.

Number	IM1
Label	**Equation Of Wall x**
Input	C_x and D_x of wall x from the user (C_x and D_x should not be at the same location) (A8)
Output	$M = \begin{pmatrix} m1 & m2 \end{pmatrix}$ and k for the equation representing the wall's line: $M \begin{pmatrix} x & y \end{pmatrix}^T = k$
Description	$C_x = (x_{C_x}, y_{C_x})$ is the position of wall x's starting vertex. (m). $D_x = (x_{D_x}, y_{D_x})$ is the position of wall x's ending vertex. (m). $M = \begin{pmatrix} m1 & m2 \end{pmatrix}$ is the coefficient matrix of the equation of wall x, in which $$m1 = \begin{cases} -\frac{y_{D_x} - y_{C_x}}{x_{D_x} - x_{C_x}} & \text{if } x_{D_x} - x_{C_x} \neq 0 \\ 1 & \text{else} \end{cases}$$ and $$m2 = \begin{cases} 1 & \text{if } x_{D_x} - x_{C_x} \neq 0 \\ 0 & \text{else} \end{cases}$$ k is a coefficient in the line's equation(m), and can be calculated as following: $k = m1 \cdot x_{C_x} + m2 \cdot y_{C_x} = m1 \cdot x_{D_x} + m2 \cdot y_{D_x}$
Sources	Stephen H. Friedberg (2019)
Ref. By	IM7, IM8, IM6

Derivation of the line's equation

$M \begin{pmatrix} x & y \end{pmatrix}^T = k$

$\begin{pmatrix} m1 & m2 \end{pmatrix} \begin{pmatrix} x & y \end{pmatrix}^T = k$

$m1 \cdot x + m2 \cdot y = k$

if $x_{D_x} - x_{C_x} \neq 0$:

$m2 \cdot y = -m1 \cdot x + k$

$y = -\frac{m1}{m2} \cdot x + \frac{k}{m2}$

In which $-\frac{m1}{m2}$ is the slope of the function of y against x, and $\frac{k}{m2}$ is the y-intercept of the function y against x.

For the equation of a line:

$$y = \frac{\Delta Y}{\Delta X}x + y(0)$$

Where $\frac{\Delta Y}{\Delta X}$ is the slope of the line and $y(0)$ is the value of y when x = 0. In the equation above, ΔX is the change of x-value and ΔY is the corresponding change in y-value. In RSSC, we can take the difference between the starting and the ending vertices' x-Coordinates as ΔX and take the difference between the starting and the ending vertices' y-Coordinates as ΔY, then we have:

$$\frac{\Delta Y}{\Delta X} = -\frac{m1}{m2} = \frac{y_{D_x} - y_{C_x}}{x_{D_x} - x_{C_x}}$$

For lines that are not vertical (In RSSC, $x_{D_x} - x_{C_x} \neq 0$), we can set $m2$ to 1, then:

$$y = -m1 \cdot x + k$$

$$m1 = -\frac{y_{D_x} - y_{C_x}}{x_{D_x} - x_{C_x}}$$

if $x_{D_x} - x_{C_x} = 0$, we will not be able to find $m1$ by $m1 = -\frac{y_{D_x} - y_{C_x}}{x_{D_x} - x_{C_x}}$ since we cannot take 0 as the denominator. In this case, we preliminarily set $m1 = 1$. Then:

$$k = m1 \cdot x_{C_x} + m2 \cdot y_{C_x} = m1 \cdot x_{D_x} + m2 \cdot y_{D_x}$$

$$k = 1 \cdot x_{C_x} + m2 \cdot y_{C_x} = 1 \cdot x_{D_x} + m2 \cdot y_{D_x}$$

Since $x_{D_x} - x_{C_x} = 0$, $x_{C_x} = x_{D_x}$, so

$$m2 \cdot y_{C_x} = m2 \cdot y_{D_x}$$

Also because $y_{C_x} \neq y_{D_x}$ (A8), the only solution for $m2$ is

$$m2 = 0$$

Number	IM2
Label	**Equation Of Signal Path**
Input	E and F of wall x from the user or IM4
Output	$M = \begin{pmatrix} m1 & m2 \end{pmatrix}$ and k for the equation of the line representing the signal path: $M \begin{pmatrix} x & y \end{pmatrix}^T = k$
Description	$E = (x_E, y_E)$ is the position of the signal path's starting vertex. (m). $F = (x_F, y_F)$ is the position of the signal path's ending vertex. (m). Strategy to find $m1$, $m2$, and k here is the same as in (IM1).
Sources	Stephen H. Friedberg (2019)
Ref. By	IM7, IM8, IM6

Number	IM3
Label	**Unit Normal Vector For Wall x**
Input	C_x and D_x of wall x from the user (C_x and D_x should not be at the same location) (A8)
Output	n of wall x
Description	$C_x = (x_{C_x}, y_{C_x})$ is the position of wall x's starting vertex. (m). $D_x = (x_{D_x}, y_{D_x})$ is the position of wall x's ending vertex. (m). n is the unit normal vector of wall x and can be calculated as below: $n = \begin{bmatrix} (x_{D_x} - x_{C_x}) & (y_{D_x} - y_{C_x}) \end{bmatrix} \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \cdot \frac{1}{\sqrt{(y_{D_x} - y_{C_x})^2 + (x_{D_x} - x_{C_x})^2}}$
Sources	Weisstein (2020)
Ref. By	IM4, IM5, IM7, IM8

Derivation of the equation of n

Let $A = (x_{D_x} - x_{C_x})$, let $B = (y_{D_x} - y_{C_x})$;
The vector representing wall x's line segment is then:

$$\begin{pmatrix} A & B \end{pmatrix}$$

By the definition given in (DD3), n is perpendicular to the wall, so the dot product of n and

$(A\ B)$ should be equal to 0.
proof:

$$n = \begin{bmatrix}(x_{D_x} - x_{C_x}) & (y_{D_x} - y_{C_x})\end{bmatrix} \begin{bmatrix}0 & -1 \\ 1 & 0\end{bmatrix} \cdot \frac{1}{\sqrt{(y_{D_x}-y_{C_x})^2+(x_{D_x}-x_{C_x})^2}}$$
$$n = \begin{bmatrix}A & B\end{bmatrix} \begin{bmatrix}0 & -1 \\ 1 & 0\end{bmatrix} \cdot \frac{1}{\sqrt{(y_{D_x}-y_{C_x})^2+(x_{D_x}-x_{C_x})^2}}$$

Since C_x and D_x are not at the same location (A8), we can conclude that

$$\sqrt{(y_{D_x} - y_{C_x})^2 + (x_{D_x} - x_{C_x})^2} > 0$$

Also,

$$\begin{bmatrix}A & B\end{bmatrix} \begin{bmatrix}0 & -1 \\ 1 & 0\end{bmatrix} = \begin{bmatrix}B & -A\end{bmatrix}, \text{ and}$$
$$||\begin{bmatrix}B & -A\end{bmatrix}|| = \sqrt{B^2 + (-A)^2} = \sqrt{(y_{D_x} - y_{C_x})^2 + (x_{D_x} - x_{C_x})^2}$$

So $||n|| = \frac{\sqrt{(y_{D_x}-y_{C_x})^2+(x_{D_x}-x_{C_x})^2}}{\sqrt{(y_{D_x}-y_{C_x})^2+(x_{D_x}-x_{C_x})^2}} = 1$.

Let q $= \frac{1}{\sqrt{(y_{D_x}-y_{C_x})^2+(x_{D_x}-x_{C_x})^2}}$,

$$n \cdot \begin{bmatrix}A & B\end{bmatrix} = \begin{bmatrix}B & -A\end{bmatrix} \cdot \begin{bmatrix}A & B\end{bmatrix} \cdot q$$
$$n \cdot \begin{bmatrix}A & B\end{bmatrix} = [AB + (-AB)] \cdot q$$
$$n \cdot \begin{bmatrix}A & B\end{bmatrix} = 0 \cdot q$$
$$n \cdot \begin{bmatrix}A & B\end{bmatrix} = 0$$

Number	IM4
Label	**Reflection Intersection**
Input	C_x, D_x of wall x from the user (m) Pos_{tsm}, Pos_{sp} from the user (m) n from IM3 M_x,k_x from IM1 M_p,k_p from IM2 (C_x and D_x should not be at the same location) (A8)
Output	t' $Ind_{r,x}$ $d_{rsm',sp}$
Description	$C_x = (x_{C_x}, y_{C_x})$ is the position of wall x's starting vertex (m). $D_x = (x_{D_x}, y_{D_x})$ is the position of wall x's ending vertex (m). Pos_{tsm} is the position of the transmitter (m). Pos_{sp} is the position of the sampling point (m). n is the unit normal vector of wall x given by IM3. t' is the point on wall x's plane where the signal to reflect intersects that plane (t' may not be on wall x. wall x has limited dimensions, and t' may fall outside of wall x, but still on wall x's plane) (m). $Ind_{r,x}$ is a boolean which indicates whether wall x intersects t' or not. Use C_x, Pos_{tsm}, and n to find Pos_{tsm}'s mirror point Pos'_{tsm} (refer to T2). Solve the linear system $\begin{pmatrix} M_x \\ M_p \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} k_x \\ k_p \end{pmatrix}$ for $\begin{pmatrix} x \\ y \end{pmatrix}$. x and y here are coordinates of t'. M_x and k_x in the linear system above are coefficients of the line equation for wall x. M_p and k_p in the linear system above are coefficients of the line equation for the signal path from Pos'_{tsm} to Pos_{sp}. $Ind_{r,x} = \begin{cases} 1 & \text{if } min(x_{C_x}, x_{D_x}) < x < max(x_{C_x}, x_{D_x}) \text{ and} \\ & min(y_{C_x}, y_{D_x}) < y < max(y_{C_x}, y_{D_x}) \\ 0 & else \end{cases}$ $d_{rsm',sp}$ is the Euclidean distance between the mirror of the transmitter at Pos'_{tsm} and the sampling point at Pos_{sp} (m).
Sources	Anonymous (1989)
Ref. By	IM7, IM8

Number	IM5
Label	**Transmission Intersection**
Input	C_x, D_x, and R_x of wall x from the user E, F from the user or (IM4) M_x,k_x from (IM1) M_p,k_p from (IM2) (C_x and D_x should not be at the same location) (A8)
Output	$Ind_{t,x}$ that indicates whether wall x intersects the signal's path or not.
Description	$C_x = (x_{C_x}, y_{C_x})$ is the position of wall x's starting vertex. (m). $D_x = (x_{D_x}, y_{D_x})$ is the position of wall x's ending vertex. (m). n is the unit normal vector of wall x given by IM3. Solve the linear system $\begin{pmatrix} M_x \\ M_p \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} k_x \\ k_p \end{pmatrix}$ for $\begin{pmatrix} x \\ y \end{pmatrix}$. M_x and k_x in the linear system above are coefficients of the line equation for wall x. M_p and k_p in the linear system above are coefficients of the line equation for the signal path from E to F. $Ind_{t,x} = \begin{cases} 1 & \text{if } min(x_{C_x}, x_{D_x}) < x < max(x_{C_x}, x_{D_x}) \text{ and} \\ & min(y_{C_x}, y_{D_x}) < y < max(y_{C_x}, y_{D_x}) \\ 0 & else \end{cases}$
Sources	Anonymous (1989)
Ref. By	IM6, IM7, IM8

Number	IM6
Label	**Line Of Sight Signal Strength**
Input	f of the radio signal from user $d_{tsm,sp}$ from (T1) A list of $[T_x]$ for all walls ($x = 1, 2, \cdots, N_w$) from the user A list of $[Ind_{t,x}]$ for all walls ($x = 1, 2, \cdots, N_w$) from (IM5) P_{tsm}^{dBm} from the user
Output	P_{LOS}
Description	f is the frequency of the radio signal (Hz). T_x is the transmittance of wall x. $[T_x]$ is an $(N_w \times 1)$ list of T_x for $x = 1, 2, \cdots, N_w$. $Ind_{t,x}$ is a boolean. $Ind_{t,x} = 1$ if wall x occludes the line of sight signal's path, otherwise $Ind_{t,x} = 0$. $[Ind_{t,x}]$ is an $(N_w \times 1)$ list of $Ind_{t,x}$ for $x = 1, 2, \cdots, N_w$. N_w is the total number of walls. P_{tsm}^{dBm} is the power level of the transmitter (dBm). P_{LOS} is the power of line of sight signal in W. First transfer power in dBm to power in W (DD4). Use f and $d_{tsm,sp}$ to find $FSPL$ (GD3). The power of line of sight signal can be derived as: $P_{LOS} = \frac{P_{tsm}}{FSPL} \cdot \prod_{x=1}^{N_w} T_x^{(Ind_{t,x})}$
Sources	Anonymous (1989), Wikipedia (2020a)
Ref. By	IM9, IM7

Derivation of the equation of P_{LOS}

The definition of transmittance T is the ratio of the power of radiance passing through the obstacle to the power of radiance as if there was no obstacle(DD2). If there are multiple obstacles, The power of radiance that passes through all the obstacles will be the initial power of the radiance times the percentage of power passing through the first obstacle, then times the percentage of power passing through the second obstacle and so on. So we have $\prod_{x=1}^{N_w} T_x$ in the calculation of line of sight signal strength.

The reason to take $Ind_{t,x}$ as the power of T_x is that not all of the walls appear in a signal's path. For walls not blocking the signal, we should not let them attenuate the signal in the simulation. When wall x blocks the signal, $Ind_{t,x} = 1$ (IM5), in this case $T_x^{(Ind_{t,x})} = T_x$. When wall x does not block the signal, $Ind_{t,x} = 0$ and $T_x^{(Ind_{t,x})} = 1$, meaning that no power loss happens due to wall x.

Radio signals attenuate not only due to material transmittance, but also due to travelling in space. According to (GD3), $\frac{1}{FSPL}$ is the ratio of the signal's power after travelling a distance d in free space. This attenuation should also be included in our calculation.

Considering the above, the line of sight signal strength is hence:

$$P_{LOS} = \frac{P_{tsm}}{FSPL} \cdot \prod_{x=1}^{N_w} T_x^{(Ind_{t,x})}.$$

Number	IM7
Label	**First-Order Reflected Signal Strength**
Input	f of the radio signal from user A list of $[T_x]$ for all walls $(x = 1, 2, \cdots, N_w)$ from the user A list of $[Ind_{t,x}]$ for all walls $(x = 1, 2, \cdots, N_w)$ from (IM5) R_x for wall x from the user $Ind_{r,x}$ for wall x from (IM4) t' for wall x from (IM4) P_{tsm}^{dBm} from the user Pos_{tsm} from the user Pos_{sp} from the user
Output	P_{FROS_x}
Description	f is the frequency of the radio signal (Hz). Pos_{tsm} is the position of the transmitter (m). Pos_{sp} is the position of the sampling point (m). T_x is the transmittance of wall x. $[T_x]$ is an $(N_w \times 1)$ list of T_x for $x = 1, 2, \cdots, N_w$. $Ind_{t,x}$ is a boolean. $Ind_{t,x} = 1$ if wall x occludes the line of sight signal's path, otherwise $Ind_{t,x} = 0$. $[Ind_{t,x}]$ is an $(N_w \times 1)$ list of $Ind_{t,x}$ for $x = 1, 2, \cdots, N_w$. N_w is the total number of walls. R_x is the reflectance of wall x (DD1). $Ind_{r,x}$ is a boolean indicating whether wall x intersects t' or not. (IM4) t' is the point on wall x's plane where the signal to reflect intersects that plane (IM4). (m) P_{tsm}^{dBm} is the power level of the transmitter (dBm).

Label	**First-Order Reflected Signal Strength**
Description Continued	P_{FROS_x} is the power of first-order reflected signal that travels from Pos_{tsm}, has a specular reflection at wall x , then reaches Pos_{sp} (W). Transfer power in dBm to power in W (DD4). Use f and $d_{tsm,sp}$ to find $FSPL$ (GD3). The first-order reflected signal can be divided into 2 sections: Pre-Reflection signal ($RS1$) and Post-Reflection signal ($RS2$). For Pre-Reflection signal, calculation of its power P_{RS1} is the same as calculation of P_{LOS}, but Pos_{sp} is replaced with the position of t' here. Pre-Reflection signal at t' is the source of Post-Reflection signal. With reflectance, transmittance, and path loss, the resulting power of Post-Reflection signal is then: $P_{RS2} = \frac{P_{tsm}}{FSPL_{tsm \to t'}} \prod_{i=1}^{N_w} T_i^{(Ind_{t,i})} \times R_x \times Ind_{r,i} \times \frac{1}{FSPL_{t' \to sp}} \prod_{j=1}^{N_w} T_j^{(Ind_{t,j})}$ and $P_{FROS_x} = P_{RS2}$
Sources	Anonymous (1989)
Ref. By	IM9

Number	IM8
Label	**First-Order Reflection Signal Phase Angle**
Input	f of the radio signal from user $d_{tsm,sp}$ from (T1) $d_{tsm,t'}$ from (T1) $d_{t',sp}$ from (T1)
Output	ϕ_{FORS_x}
Description	f is the frequency of the radio signal (Hz). $d_{tsm,sp}$ is the Euclidean distance between the transmitter and the receiver (m). $d_{tsm,t'}$ is the Euclidean distance between the transmitter and the point t' (m). $d_{t',sp}$ is the Euclidean distance between the the point t' and the receiver (m). t' is the point on wall x's plane where the signal to reflect intersects that plane (IM4). (m) ϕ_{FORS_x} is the phase angle of the first-order reflected signal against wall x, when taking the line of sight signal as a reference with 0rad phase angle. According to GD2, ϕ_{FORS_x} can be found by the following equation: $\phi_{FORS_x} = \frac{2\pi f(d_{tsm,t'} + d_{t',sp} - d_{tsm,sp})}{c}$
Sources	Anonymous (1989), Wikipedia (2020a)
Ref. By	IM9

Derivation of the equation of ϕ_{FORS_x}

$\Delta\phi = \frac{2\pi\Delta d}{\lambda}$

$$\phi_{FORS_x} - \phi_{LOS} = \frac{2\pi\Delta d}{\lambda}$$

$$\phi_{FORS_x} - \phi_{LOS} = \frac{2\pi f\Delta d}{c}$$

$$\phi_{FORS_x} - \phi_{LOS} = \frac{2\pi f(d_{tsm,t'} + d_{t',sp} - d_{tsm,sp})}{c}$$

$$\phi_{FORS_x} = \frac{2\pi f(d_{tsm,t'} + d_{t',sp} - d_{tsm,sp})}{c} \text{ as } \phi_{LOS} = 0$$

Number	IM9
Label	**Received Signal Strength**
Input	P_{LOS} from (IM6) $[P_{FROS_x}]$ for $x = 1, 2, 3, \cdots, N_w$ from (IM7) $[\phi_{FORS_x}]$ for $x = 1, 2, 3, \cdots, N_w$ from (IM8)
Output	P_{sp}^{dBm}
Description	P_{LOS} is the line of sight signal strength (W). P_{FROS_x} is the first-order reflected signal strength (W). ϕ_{FORS_x} is the phase angle of the first-order reflected signal against wall x, when taking the line of sight signal as a reference with 0rad phase angle. According to T1, $P_{sp}e^{i\phi_{sp}} = P_{LOS}e^0 + \sum_{x=1}^{N_w} P_{FROS_x}e^{i\phi_{FORS_x}}$ $P_{sp}^{dBm} = 30 + 10\log_{10}(\frac{P_{sp}}{1W})$
Sources	Wikipedia (2020e), Wikipedia (2020a)
Ref. By	GS1

4.2.6 Input Data Constraints

Table 1 shows the data constraints on the input output variables. The column for physical constraints gives the physical limitations on the range of values that can be taken by the variable. The column for software constraints restricts the range of inputs to reasonable values. The software constraints will be helpful in the design stage for picking suitable algorithms. The constraints are conservative, to give the user of the model the flexibility to experiment with unusual situations. The column of typical values is intended to provide a feel for a common scenario. The uncertainty column provides an estimate of the confidence with which the physical quantities can be measured. This information would be part of the input if one were performing an uncertainty quantification exercise.

The specification parameters in Table 1 are listed in Table 2.

4.2.7 Properties of a Correct Solution

A correct solution must exhibit the law of conservation of energy. This means that P_{sp}^{dBm} should always be lower than P_{tsm}^{dBm}.

Table 1: Input Variables

Var	Physical Constraints	Software Constraints	Typical Value	Uncertainty
T_x	$0 < T_x < 1$	N/A	0.1	10%
R_x	$0 < R_x < 1$	N/A	0.6	10%
P_{tsm}^{dBm}	N/A	$P_{min}^{dBm} \leq P_{tsm}^{dBm} \leq P_{max}^{dBm}$	0dBm	15%
f	N/A	$f_{min} \leq f \leq f_max$	2.4×10^9Hz	10%
x_{C_x}	N/A	$x_{min} \leq x_{C_x} \leq x_{max}$	0m	10%
y_{C_x}	N/A	$y_{min} \leq y_{C_x} \leq y_{max}$	0m	10%
x_{D_x}	N/A	$x_{min} \leq x_{D_x} \leq x_{max}$	0m	10%
y_{D_x}	N/A	$y_{min} \leq y_{D_x} \leq y_{max}$	0m	10%
N_w	N/A	$0 \leq P_{tsm}^{dBm} \leq \times 10^{11}$	0m	10%

Table 2: Specification Parameter Values

Var	Value
P_{max}^{dBm}	15 dBm
P_{min}^{dBm}	-30 dBm
f_{min}	30 Hz
f_{max}	3×10^{11} Hz
x_{min}	-20 m
x_{max}	20 m
y_{min}	-20 m
y_{max}	20 m

5 Requirements

This section provides the functional requirements, the business tasks that the software is expected to complete, and the nonfunctional requirements, the qualities that the software is expected to exhibit.

5.1 Functional Requirements

Table 3: Output Variables

Var	Physical Constraints
P_{sp}^{dBm}	$-120 < P_{sp}^{dBm} < 0$
Pos_{sp}	N/A

R1: RSSC shall input the data shown in Table 4, and store the data.

R2: Verify that the number of starting points, number of ending points, number of directional transmittances and directional Reflectances of walls are consistent; verify that the input Cartesian position coordinates, transmitter power level and signal frequency are within appropriate range.

R3: Calculate and output the value of P_{sp}^{dBm}.

R4: Verify the value of P_{sp}^{dBm} in the final result. The P_{sp}^{dBm} should never be greater than P_{tsm}^{dBm}.

R5: Generate a file storing P_{sp}^{dBm} at every sampling point the user provide.

Table 4: Required Input Variables

Symbol	Description	Units
Pos_{tsm}	Cartesian position coordinates of the transmitter	m
$[Pos_{sp}]$	(multiple entities) Cartesian position coordinates of sampling points	m
$[C]$	(multiple entities) Cartesian position coordinates of the starting point of walls	m
$[D]$	(multiple entities) Cartesian position coordinates of the ending point of walls	m
$[T]$	(multiple entities) Directional transmittances of walls	-
$[R]$	(multiple entities) Directional Reflectances of walls	-
P_{tsm}^{dBm}	Power level of the transmitter	dBm
f	frequency of the signal	Hz

5.2 Nonfunctional Requirements

Correct: The outputs of RSSC satisfies the description in subsubsection 4.2.7.

Verifiable: Easy to test and verificate.

Portable: Able to run in different environments.

Maintainable: Proper documents should be included in this project.

Understandable: Program of RSSC should be organized, well commented, and easy to understand.

6 Likely Changes

LC1: The assumption that 2nd-order or higher order reflections are negligible (A9) is too weak. High order reflections of radio signals can have complicated behaviors. For example we cannot simulate the effect of a corner reflector with only direct and 1st-order reflected signals.

LC2: Oriented antennas are commonly used on transmitters to enhance the signal strength toward some designated directions. To simulate this scenario, we may change the assumption (A4) and introduce directional gains to transmitters.

LC3: Another likely change is the assumption that floor and ceiling do not reflect radio signals (A2). This assumption was made to simplify the analysis, but floor and ceiling are strong reflectors. Besides, floor and ceiling reflections are regular and easy to integrate into the 2-D system.

7 Unlikely Changes

LC4: The assumption that walls have positive lengths (A8) is unlikely to change because a wall with zero or negative length is meaningless both for analysis and in the real world.

8 Traceability Matrices and Graphs

The purpose of the traceability matrices is to provide easy references on what has to be additionally modified if a certain component is changed. Every time a component is changed, the items in the column of that component that are marked with an "X" may have to be modified as well. Table 7 shows the dependencies of theoretical models, general definitions, data definitions, and instance models with each other. Table 5 shows the dependencies of instance models, requirements, and data constraints on each other. Table 6 shows the dependencies of theoretical models, general definitions, data definitions, instance models, and likely changes on the assumptions.

	IM1	IM2	IM3	IM4	IM5	IM6	IM7	IM8	IM9	R1
IM1										X
IM2										X
IM3										X
IM4			X							X
IM5			X							X
IM6	X	X			X					X
IM7	X	X	X	X	X	X				X
IM8	X	X	X	X	X					X
IM9						X	X	X		X
R1										
R2										
R3	X								X	
R4										
R5									X	

Table 5: Traceability Matrix Showing the Connections Between Requirements and Instance Models

The purpose of the traceability graphs is also to provide easy references on what has to be additionally modified if a certain component is changed. The arrows in the graphs represent dependencies. The component at the tail of an arrow is depended on by the component at the head of that arrow. Therefore, if a component is changed, the components that it points to should also be changed. Figure **??** shows the dependencies of theoretical models, general definitions, data definitions, instance models, likely changes, and assumptions on each other. Figure **??** shows the dependencies of instance models, requirements, and data constraints on each other.

9 Values of Auxiliary Constants

This section contains the standard values that are used for calculations in RSSC .

Symbol	**Description**	**Value**	**Units**
c	speed of light	3×10^8	$\mathrm{m\,s^{-1}}$

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
T1	X										
T2			X				X				
T3											
GD1											X
GD2						X					
GD3				X	X						
DD1			X				X				
DD2						X					
DD3	X						X				
DD4											
IM1	X						X	X			
IM2	X							X			
IM3	X										
IM4	X						X	X			
IM5	X						X	X			
IM6						X					
IM7		X									
IM8		X									X
IM9		X	X						X	X	
LC1									X		
LC2				X							
LC3		X									

Table 6: Traceability Matrix Showing the Connections Between Assumptions and Other Items

	T1	T2	T3	GD1	GD2	GD3	DD1	DD2	DD3	DD4	IM1	IM2	IM3	IM4	IM5	IM6	IM7	IM8	IM9
T1																			
T2									X										
T3																			
GD1																			
GD2	X																		
GD3	X		X																
DD1																			
DD2																			
DD3																			
DD4																			
IM1																			
IM2																			
IM3									X										
IM4	X	X											X						
IM5													X						
IM6	X					X		X		X	X	X			X				
IM7	X	X				X	X	X		X	X	X	X	X	X	X			
IM8	X				X						X	X	X	X	X				
IM9	X			X												X	X	X	

Table 7: Traceability Matrix Showing the Connections Between Items of Different Sections

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