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Item Type	Meetings and Proceedings
Authors	Rao, Shashank;Walker, Jacqueline
Citation	OCEANS 2023, pp. 1-7
Publisher	IEEE
Download date	2026-03-08 03:52:46
Item License	<a href="https://creativecommons.org/licenses/by-nc-sa/4.0/">https://creativecommons.org/licenses/by-nc-sa/4.0/</a>
Link to Item	<a href="https://doi.org/10.34961/researchrepository-ul.25047260">https://doi.org/10.34961/researchrepository-ul.25047260</a>

# Wireless Network for Offshore Renewable Energy Installations- Software Defined Radio Approach

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**Abstract**— The paper first reviews the wireless communication systems used in the offshore environment. It focuses on Software Defined Radio (SDR) as a wireless solution for offshore renewable energy installations (wind, solar, and wave farms). Line of sight links, network topologies, hybrid structures, spatial diversity, and multiplexing are considered to improve throughput. The final implementation proposed is a remotely managed SDR-based network that supports inter-device communication to control and monitor offshore energy installations. The SDR platform facilitates flexible network design (such as adding new sensors and actuators without modifying the underlying network) over the widely used Ethernet-based network. GNU Radio software is used for the development of the SDR. USRP SDR will be used to carry out offshore experiments. 3D models of Arklow wind park turbines are created in Sketchup, then imported to MATLAB where the wireless network within the wind farm is simulated using ray tracing. USRP SDR will be used to carry out offshore experiments.

**Keywords**— Maritime Communications, Software Defined Radio, GNU Radio, Ray tracing, MATLAB.

## I. INTRODUCTION

Globally, the coasts of Ireland have some of the most energetic winds and waves, making it an ideal location to harness offshore energy. With only one functioning offshore energy installation- Arklow Bank Wind Park, Ireland is yet to explore its offshore resources to maximum potential. One of the key takeaways of Ireland's Climate Action Plan is to produce 80% of electricity through renewables by 2030, including 5GW of offshore wind and 8GW of Onshore wind and achieve net-zero greenhouse gas emissions by 2050 [1]. Over 30 offshore wind projects are in progress, totaling 29GW [2]. Though much of the offshore energy focus in Ireland is on the wind, the wave energy resources available have the potential to satisfy 75% of the country's electricity needs. Still, most designs are in the research stages [3].

For wind energy, the key advantages of offshore energy installation are the high wind speed, consistent wind direction, and larger equipment size, thus leading to efficient and significantly higher energy generation than onshore installations. Operation and maintenance of these wind turbines costs are about 25–30% of the total lifecycle cost (planning, equipment, installation, operation, maintenance, and decommissioning) [4].

Real-time monitoring of the equipment can reduce the chances of breakdown, lowering the cost of maintenance and so lower overall lifecycle costs. A requirement of real-time monitoring is communicating the results back to the base, which is a more significant issue for offshore energy installations than onshore installations. Solutions may include undersea cables to shore or point-to-point wireless solutions. Monitoring a widely spread offshore structure almost demands wireless solutions. Although wireless systems have significant advantages, they have reliability, bandwidth, latency, and security issues [5]. In section 2 we review maritime communication systems in brief, section 3 introduces an SDR based approach to wireless communication, sections 4 and 5 discuss various approaches to setting up the wireless network and its configurations, Section 6 introduces GNU Radio and how to design and create a wireless network in software and section 7 explains in detail about the ray tracing approach to model an offshore wind turbine.

## II. MARITIME COMMUNICATION SYSTEMS

### A. Marine Radio Systems

Vessels are equipped with two-way radio transceivers and are used for communication between ships and the shore. Although the data rates are low, the signals can travel an extensive range [6] as seen in Table 1.

TABLE I. MARITIME RADIO SYSTEMS

System	Technology	Range (in km)	Data rate (in kbps)
Navtex	MF/HF	460-740	0.1
NAVDAT	MF	463-556	7-18
AIS	VHF	75-111	9.6
ASM	VHF	28-120	19.2
VDE-TER	VHF	37-92	38.4-307.2
VDE-SAT	LEO Satellite	Global	240
VHF DSC	VHF	120	1.2
Digital HF	HF	370	22

### B. Marine Satellite Systems

Satellites are the only viable option for accessing Internet services with broad coverage in the maritime environment. They can provide internet services with high data rates but are susceptible to weather conditions, and the cost of equipment and data services are expensive [6].

TABLE II. MARITIME SATELLITE SYSTEMS

Satellite	Technology	Range (in km)	Data rate (in kbps)
Inmarsat 4	GEO Satellite	Global, except the polar areas	492
Inmarsat 5	GEO Satellite	Global, except the polar areas	16,000
Iridium	LEO Satellite	Global	134
Iridium Next	LEO Satellite	Global	1,500

### C. Marine Broadband Systems

The maritime broadband systems are those that provide us with data rates in the range of Mbps. Due to high data rates, the range of maritime broadband systems is limited to 50km [6].

TABLE III. MARITIME BROADBAND SYSTEMS

Satellite	Protocol	Range (in km)	Data rate (in kbps)
WISEPORT	WiMAX	15	5,000
TRITON	WiMAX	14.2 (ship-to-shore) 8.66 (ship-to-ship)	6,000
MariComm	LTE, WLAN, WLAN AP	10 (LTE) 20 (WLAN) 48.7 (WLAN AP)	Up to 10,000
BLUECOM+	LTE IEEE 802.11g	10 (LTE) 40 (IEEE 802.11g)	Up to 3200

Marine radio systems are mainly used for communication and are of low bandwidth. The satellite systems have higher latency and are quite expensive. The marine broadband systems provide sufficient bandwidth for transfer of data between wind turbines if the turbines are placed within the range of the system but these mainly focus on mobile users, which makes it a requirement and efficient to develop a separate wireless network for wind turbines.

### III. PURPOSE OF SDR IN AN OFFSHORE ENVIRONMENT

Software Defined Radio (SDR) is built upon a programmable transceiver that can be programmed to support every wireless technology within the SDR range without making changes to the hardware. Standards such as LTE, 4G, 5G, WiFi-11ac/a/ax/b/g/n, Bluetooth, Zigbee, WiMAX, etc., can be built with the same SDR [7]. An SDR, a computer that can run specialized SDR design software such as GNU Radio, and an antenna setup are sufficient to build the SDR network.

Sensor data from the offshore environment can be received and actuators in the offshore energy installation can be controlled via the SDR-computer setup and software changes may be made remotely over the wireless network without making any changes to the hardware. This type of flexible design is impossible in the traditional ethernet-based network. Because wireless systems for the offshore environment are not widely implemented, an SDR-based network is helpful in testing various protocols, frequencies, modulation schemes, etc., and the results can be used to develop future offshore wireless systems [7].

For example, the global control of Wave Energy Converters (WEC) leads to up to 10% more efficient energy conversion over independent control. To achieve global control, we require

real-time model parameters from all the WECs in the installation to model the Power Take-Off Unit (PTO) responsible for energy conversion [8]. Similarly, studies have shown a 1.2% increase in energy conversion efficiency when the wind turbines were modeled as a whole rather than individually. An increase in efficiency can be achieved without changing the hardware or location of the existing wind turbines but rather by computing an optimal yaw angle to reduce the wake losses by making software changes [9]. A 1.2% increase in energy efficiency could power additional 3 million homes without modifying the existing infrastructure [10].

The SDR network will receive model parameters from the sensors in the network wirelessly from every other WEC or Wind turbine in the farm. Then, the computer computes the PTO forces or the optimal yaw angle required for efficient energy conversion. The SDR-computer setup is not only responsible for global control but is also responsible for transmitting the necessary data back to the base station on shore. Similarly, sensor data from offshore wind energy turbines can be received and monitored continuously, potentially providing warning of maintenance issues.

### IV. DESIGN CONSIDERATIONS

#### A. Line of Sight Links

Point-to-point (PTP) Line-of-sight (LOS) communication link can be established from shore to offshore installation using two highly directional antennas. The average hub height of offshore turbines is about 100m and is expected to get taller in the future, giving wireless communication links the advantage of having no obstacle in the Fresnel zone [11].

Offshore wind hybrid installations (wind-wave, wind-solar, wind-wave-solar) backed by the European Union are favored due to consistent power output, higher baseload, reduced cost, and LOS communication links [12].

#### B. Network Topologies

Consider each wind turbine in the wind farm as a node, and the node connected by the PTP link to the shore is the gateway. The typical arrangement of an offshore wind farm is a grid-like pattern to save space. If you look at the structure, there would be no PTP links between the nodes and gateway, and the nodes themselves cause an obstruction. For a grid-like arrangement, a wireless mesh network makes more sense. With a few hops, the signal can reach end-to-end. A star topology would make more sense when you can establish a PTP link between the nodes and gateway. In some cases, a hybrid of mesh and star topologies, called cluster-tree topology, could be used with an additional node (router). The router connects the nodes in a star topology and connects with other routers and the gateway in a mesh topology [13].

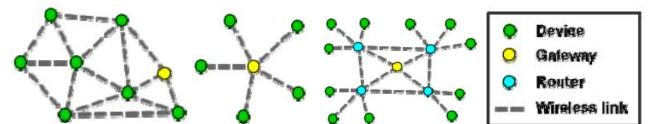


Fig. 1. Mesh, Star and Cluster-tree topology (from left to right)

## V. PROPOSED SDR-BASED MARITIME NETWORK

Each network shown in Fig. 2 is an SDR Network, each network for a wind turbine structure. The SDR network controls the actuators and receives data from the sensor nodes using one of the low power Zigbee, NB-IoT, or LoRa standard-based wireless technologies. The SDR network connects to other SDR Networks and the base station using a high-speed PTP and LOS microwave link using LTE or WiMAX and, in some cases, VHF when the link quality is affected by weather conditions.

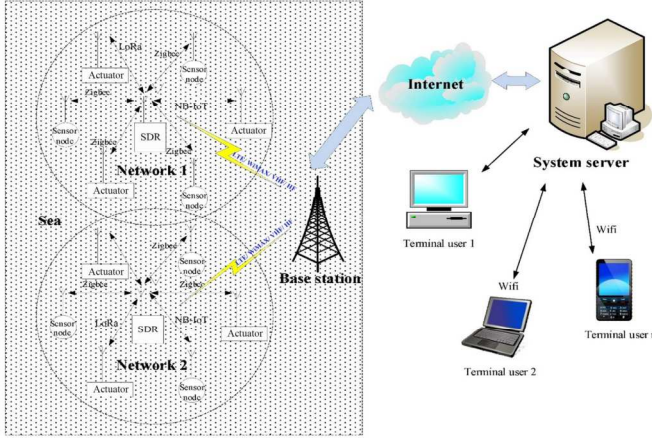


Fig. 2. Proposed SDR-Based Network

The base station connects the offshore SDR network to the internet and the real-time information is stored on a system server. We can access this data using a PC with access to the system server and also modify the SDR remotely. One way to do this would be using a Raspberry pi computer connected to the SDR running GNU Radio and accessing it via the wireless network through SSH and remote desktop.

## VI. GNU RADIO FLOWGRAPHS

Before we perform actual experiments in the offshore environment, we will build the SDR using GNU Radio, open-source software which has a graphical user interface called GNU Radio Companion (GRC) to build flowgraphs using existing signal processing blocks. The preferred operating system for software development is Linux [14].

In a wireless environment, there is more than one path for the signal to reach the receiver. Multiple versions of the same signal are received with a delay causing the echoes to overlap at the receiver leading to intersymbol interference (ISI) and bit errors. The frequency distortion caused due to multipath can be combated by pulse shaping using the Root Raised Cosine (RRC) Filter at both the transmitter and receiver and an equalizer at the receiver.

We simulate a wireless channel in GNU radio using a channel model block. The parameters of this block are Noise voltage- the AWGN noise level as a voltage, Frequency offset- the normalized frequency offset, Epsilon- the sample timing offset between the transmitter and receiver clocks. Taps- the taps of an FIR filter that emulate multipath channels.

We use the flowgraph as shown in Fig. 3, to generate the taps, which simulate a multipath channel. An awgn noise source

is generated, and the frequency response (before and after channel model block) is observed as in Fig. 4. Now, we vary the individual values of taps (between  $0 \pm 0j$  and  $1 \pm 1j$ ) and notice frequency selective fading. Once we have obtained a frequency fading channel, we record the values of the taps and feed these values to the channel model block [12]. We generate 4 taps-  $[1.0, 0.5-0.25j, 0.50 + 0.10j, -0.3 + 0.2j]$  to model 4 multipaths.

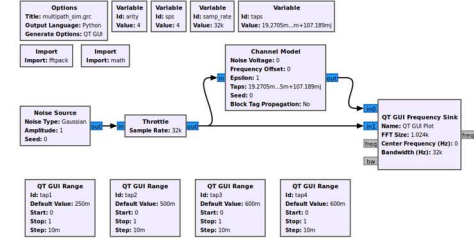


Fig. 3. Flowgraph to obtain taps to generate a multipath channel

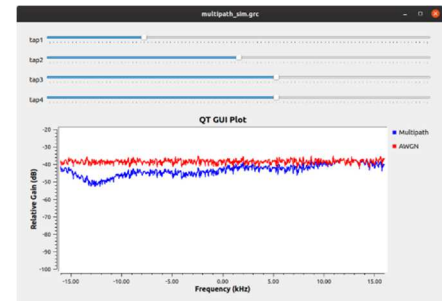


Fig. 4. Simulation of frequency fading multipath channel using taps

In the next GNU Radio Flowgraph, we have simulated a transceiver with QPSK (Quadrature Phase Shift Keying) Signal. We vary parameters of the channel model block- the AWGN noise voltage between 0 and 1, the frequency offset between -0.1Hz and 0.1Hz, the timing offset between -0.1s and 1.001s. We use a Polyphase Clock sync block at the receiver to perform clock recovery and RRC Filtering, A Constant Modulus Algorithm (CMA)- blind equalizer to remove the effects of multipath fading, which works well with signals having constant amplitude (M-PSK). In the case of QAM Signals, we would prefer a Least Mean Squared Decision- Directed (LMS-DD) equalizer. We use the Costas loop block for carrier recovery, phase, and fine frequency correction. The flowgraph of QPSK Modulation with the blocks mentioned above are shown in Fig. 5, and the outputs are shown in Fig. 6.

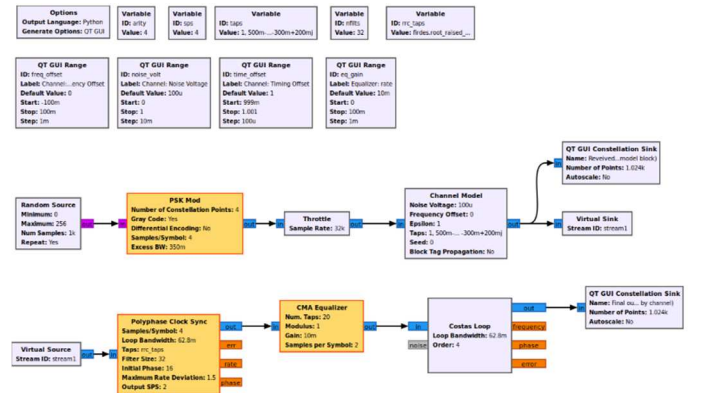


Fig. 5. GNU Radio Flowgraph modelling Channel Imperfections

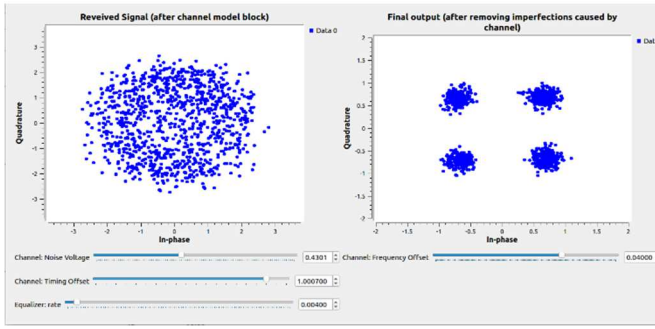


Fig. 6. Plots of Received Signal after the channel model block and the final output required for successful demodulation (after removing imperfections caused by channel).

Further, the channel model block will be used to model the offshore transmission channel. Specific features of the offshore transmission channel model may be implemented by developing an OOT (Out of tree) block. The wireless protocols, such as 4G, 5G, WiMAX and Zigbee under consideration, will be tested on the simulation testbed. In order to obtain realistic estimates of filter taps for the channel model block, we require to model an offshore wind turbine of specifications that of a real wind farm. We will then use USRP N210, an SDR by Ettus Research to conduct the experiments in the offshore environment. The development of this USRP SDR is supported on Windows, Linux, and macOS. Several frameworks, such as GNU Radio, MATLAB, LabVIEW, and Simulink, can be used to build and modify the SDR.

## VII. WIND TURBINE 3D MODELLING AND RAY TRACING

### A. Ray Tracing

Ray Tracing is a popular method for Radio Frequency analysis and channel modelling as modern day communication systems operate in the GHz range. Theoretical and empirical models estimate path loss based on range, and are valid only for those environments that closely resemble the modelling environment [15] [16]. As a result, these models usually do not provide precise temporal or spatial information.

Unlike these models, ray tracing models are specific to the 3-D environment and transceiver sites and can incorporate temporal modelling. A Ray Tracing method is therefore appropriate for building a multipath channel for wireless communication within the Wind Farm as the dimensions and locations of the turbines are known. The field measurements to calculate path loss and receiver strength is costly and difficult to obtain for an offshore environment making this technique much more efficient. The 3D model of the wind farm can be generated by using tools such as Sketchup and imported to MATLAB for ray tracing

### B. 3D Model Arklow Bank Wind Park

A 3D Model of a wind turbine is built using Sketchup- a 3D modelling Computer-Aided Design program for a broad range of drawing and design applications. The turbine modelled follows the dimensions of the Arklow Bank Wind Park Turbine with the following specifications [17].

- Hub Height (HH): 73.5 meters (241 feet)
- Tower Height (TH): 70.5 meters (231 feet)
- Tower Diameter (TD 1 and TD 2): 5 meters (16 feet) at the bottom; 3 meters (10 feet) at the top
- Blade Length (BL): 50.5 meters (165 feet)
- Rotor Diameter (RD): 104m (341 feet)

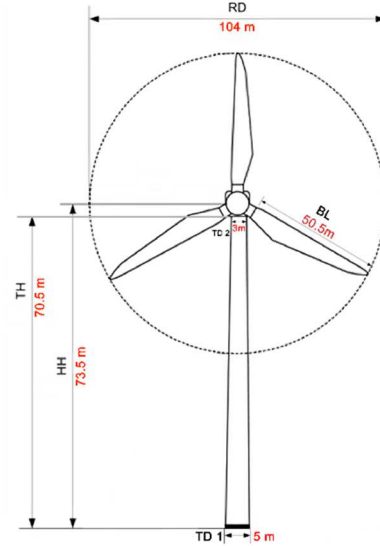


Fig. 7. Arklow Bank Wind Park Turbine dimensions

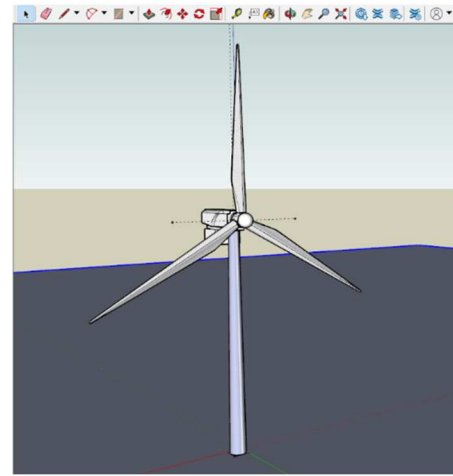


Fig. 8. 3D Model of Arklow Bank Wind Park Turbine in Sketchup

Where the Turbine Angle  $\phi_{\text{turb}}$  is the angle made between North and the turbine axis as in Fig. 9; in cartesian coordinates, it is the angle between the Y-axis and the turbine axis in a clockwise direction.

The blade azimuth angle or blade angle  $\phi_{r,B}$  is the angle made between the vertical upward direction and the first blade as in Fig. 9; in cartesian coordinates, it's the angle between the Z-axis and the first turbine blade in a clockwise direction [18] [19].

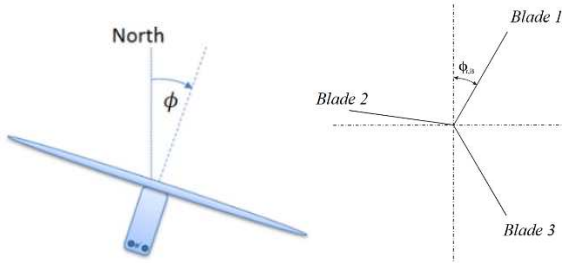


Fig. 9. Representation of Turbine angle  $\phi_{\text{turb}}$  and Blade angle  $\phi_{r,B}$ .

### C. Methodology

The aim is to find the path loss for each of the rays and obtain the signal strength at the receiver when a transmitter (N210 SDR which has a transmit power of 20dBm and receiver sensitivity of -130dBm [20] [21]) is placed on the tower of a rotating wind turbine and a receiver (also N210 SDR) placed 600m apart (the turbines are placed 600m apart in Arklow Wind Park) [17]. The path loss for each ray and the total received signal strength varies due to obstruction of the rays due to the blades and reflection from the sea water surface.

3D models of wind turbine for each of the Blade Angles,  $1^\circ$  to  $120^\circ$  (blade angles  $121^\circ$  to  $240^\circ$  and  $241^\circ$  to  $360^\circ$  are the same as  $1^\circ$  to  $120^\circ$ ) are created in SketchUp and imported to MATLAB.

The 3D model is defined in cartesian coordinate system in MATLAB. To simulate Turbine Angles, we place the transmitter on the x-y plane facing North ( $0^\circ$  being the y axis) around the turbine tower ( $1^\circ$  to  $360^\circ$ ) and receiver perpendicular to corresponding transmitter in anticlockwise direction which is equivalent to the turbine rotating clockwise. In Fig. 10 we show simulated rays for Turbine Angle  $0^\circ$  ( $360^\circ$ ) and  $270^\circ$ ,  $0^\circ$  Turbine angle ray is along the Y-axis (represented using green line) and  $270^\circ$  Turbine angle ray being along the X-axis (represented using red line).

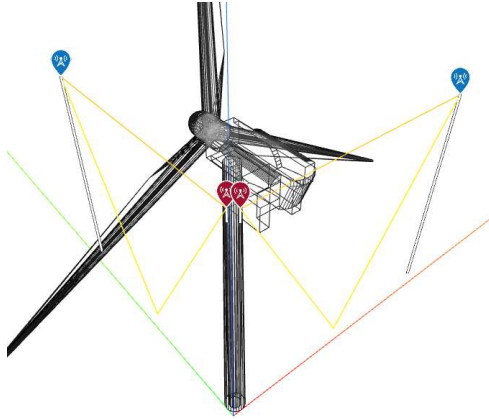


Fig. 10. Simulated Rays at turbine angle  $0^\circ$  and  $270^\circ$ .

The wind turbine is considered to be made of E-Glass Fiber with an electrical conductivity of  $10^{-12}$  S/m and relative permittivity of 6.13 and the bottom surface is considered to be sea water with an electrical conductivity of 6 S/m and relative permittivity of 81 [22][23][24][25].

### D. Results

Path loss is obtained for each of the rays for Turbine Angles of  $1^\circ$  to  $360^\circ$  and Blade Angles  $1^\circ$  to  $120^\circ$ . The rays can be categorized into four types,

- Line of Sight Rays (LOS): Rays that directly reach the receiver without any interactions.
- Sea Reflected (SR): Rays that interact with the sea surface only before reaching the receiver.
- Turbine and Sea Reflected (TSR): Rays that interact with the turbine and the sea surface before reaching the receiver.
- Turbine Reflected (TR): Rays that interact with the turbine only before reaching the receiver.

The path loss for rays at 2.4GHz, antenna height of 62m, a distance between wind turbines of 600m and Transmitter power of 20dBm at blade angle  $30^\circ$  and  $60^\circ$  is shown in the Fig. 11 and Fig. 12 respectively.

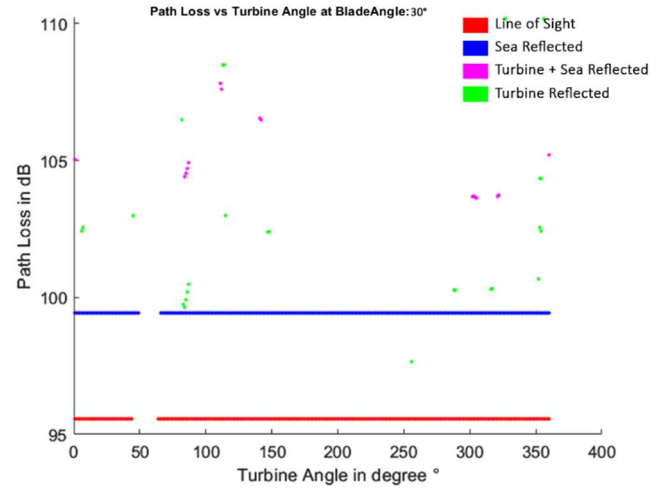


Fig. 11. Path loss vs Turbine Angle at Blade Angle of  $30^\circ$

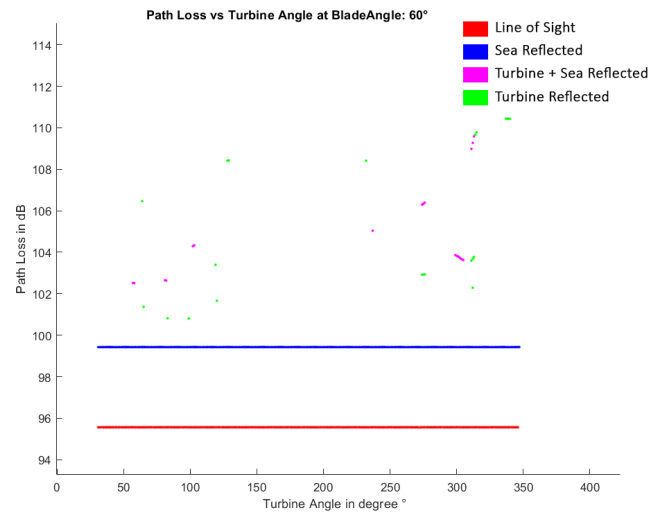


Fig. 12. Path loss vs Turbine Angle at Blade Angle of  $60^\circ$

The Received Strength is calculated in dBm using link budget form of Friis equation and considering multipath interference by using a phasor sum and the gains of the antenna and transceivers. The Fig 13 and Fig. 14 shows Rx Signal Strength at all Turbine and Blade Angles for the same.

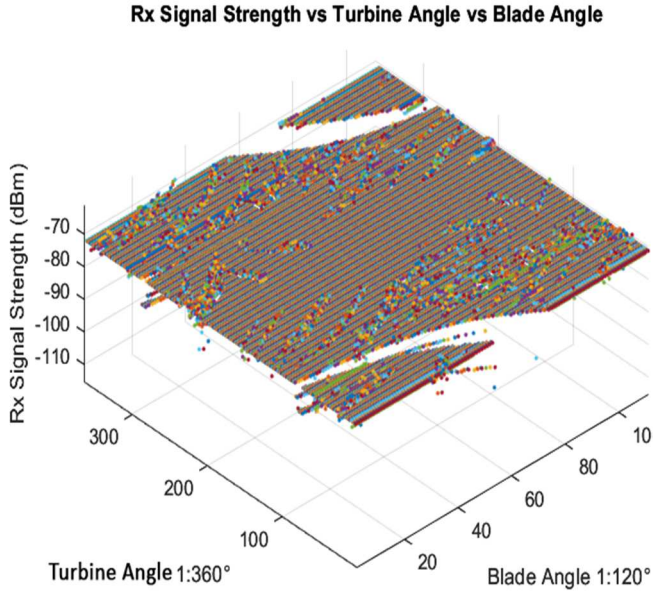


Fig. 13. Rx Signal Strength vs Turbine Angle vs Blade Angle

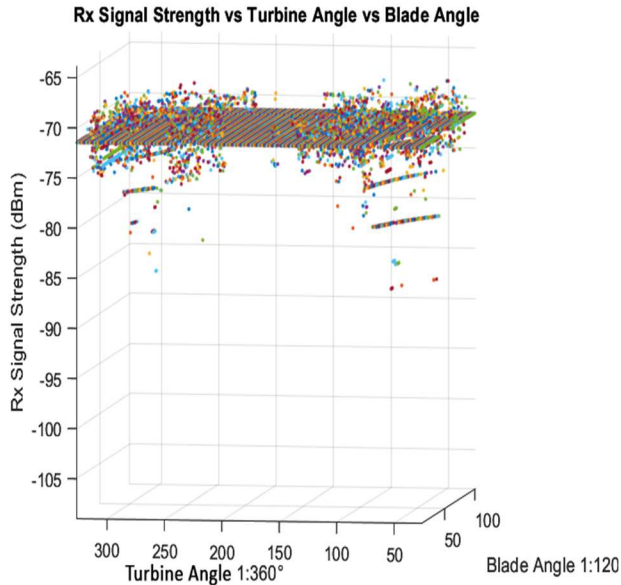


Fig. 14. Rx Signal Strength vs Turbine Angle vs Blade Angle

Average Rx signal strength for a particular height is calculated by summing all the Rx signal strengths in mW and dividing by 43,200 (360 x 120) and converting it back to dBm. Figure shows Average Rx Signal Strength vs Antenna Height at 2.4GHz frequency, a distance of 600m between wind turbines and tabulated in Table 4 along with the total number of each of the ray types present at that particular antenna height.

TABLE IV. SIGNAL STRENGTH VS ANTENNA HEIGHT

Antenna Height (in m)	Average Rx Signal Strength (in dBm)	Total Null Rays	Total LOS Rays	Total SR Rays	Total TSR Rays	Total TR Rays
67	-73.0688	13041	28355	28778	2887	5489
66	-81.6959	2870	28612	39795	3455	6209
64	-76.7161	2658	39866	40138	4919	3332
62	-71.7841	2417	40202	40445	2379	3225
60	-77.2729	2093	40605	40818	1548	2272
58	-82.0327	1812	40967	41169	1232	1829
52	-71.6454	1222	41714	41846	890	1321
48	-83.068	957	42045	42135	712	1209
44	-75.3636	752	42300	42374	478	721
20	-74.3351	0	43200	43200	53	104
18	-75.3338	0	43200	43200	47	91

Receiver signal strength obtained is based on the coherent phasor sum of individual path losses of rays at each blade angles and turbine angles. Meaning, both the 3D model (Spatial information) and the multipath delays (Temporal information) is considered to obtain the Received signal strength, which is then used to calculate the average and is tabulated in Table 4.

From the data obtained, it's seen clearly that majority of the Null rays (rays that are obstructed by the turbine blades, seen as a white patch in Fig. 13) are obtained around 0° turbine angle as expected. Also from Table 4, the number of LOS rays increase as antenna height increases and the Null rays decrease as the antenna height reduces which is expected. Higher the transmit frequency for the same height greater is the attenuation and is tabulated in Table 5.

TABLE V. TRANSMIT FREQUENCY VS AVERAGE RX SIGNAL STRENGTH

Antenna Height (in m)	Transmit Frequency	Average Rx Signal Strength (in dBm)
62	800 MHz	-61.5947
62	2.4 GHz	-71.7841
62	5 GHz	-83.8734

### VIII. CONCLUSION AND FUTURE WORK

From the ray tracing results it's clear that the received signal strength is not only dependent on the antenna height but also dependent on the multipath delays due to moving turbine and its blades. We have tabulated average received signal strength for about 11 antenna heights, but the same technique can be followed for all other heights. Filter taps can be generated for each of the blade angle-turbine angle pair and stored in a lookup table which can then be used in the channel model block of the GNU Radio to simulate the multipath channel. The 3D model imported to MATLAB being static doesn't model the changing state of the sea surface. The sea surface is flat in our model. Different sea states can be considered in future models.

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