

Diffractive NLOS Microwave Backhaul for Rural Connectivity Network as a Service Solution Group

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Authors

Julius Kusuma

Research Scientist, Facebook Connectivity jkusuma@fb.com

Erik Boch

Wireless Subject Matter Expert Consultant, Facebook Connectivity eboch@fb.com

Philip Liddell

Connectivity Program Manager, Facebook Connectivity pliddell@fb.com



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1. Introduction

Facebook Connectivity's mission is to enable better, broader global connectivity to bring more people online to a faster internet. We collaborate with the industry, including telecom operators, community leaders, technology developers, and researchers in order to find solutions that are scalable and sustainable.

1.1 Rural Connectivity Challenges

In many rural/deep-rural areas around the world, mobile access is the only viable option for internet connectivity, yet many of these areas still don't have access to mobile connectivity. The traditional technologies that bring fast, and reliable mobile connectivity to urban areas and higher-income countries are simply not economically viable for many remote communities.

According to the most recent data from the GSMA, there are still 750 million people globally living outside of areas covered by mobile broadband networks. This lack of coverage is particularly concentrated in rural and remote areas. In many of those areas, network deployment also has the added challenges of contending with lack of basic infrastructure, such as roads, water, and electricity.

1.2 Wireless Backhaul Potential and Challenges

One important element of rural connectivity is backhaul — the links that connect remote sites to the core network of the internet. There are three prevailing options to provide backhaul to rural & deep-rural communities:

- 1. Fiber
 - a. Typical fiber deployments target larger communities
 - b. Provides the highest capacities
 - c. Usually the most expensive option
 - d. Time-consuming to deploy, particularly where there is no existing infrastructure (i.e., electric poles to string fiber, conduiting, and other factors).
- 2. Satellite





- a. Typically applied to very small communities using GEO technology
- b. Cost-effective GEO technology suffers from low data rates
- 3. Wireless
 - a. High frequency terrestrial microwave radio
 - b. Typically operated in the 5.8 GHz to 8 GHz frequency range
 - c. Provides high capacity, low cost, and quick deployment

Today, the practice of carrier-grade production terrestrial microwave backhaul design is based primarily on clear line-of-sight (CLOS) design. When CLOS is not available, then the network designer will typically opt to implement repeater design topologies, which drives up costs due to the incremental tower requirements, or the use of intermediate-site passive repeaters. Both of these strategies often cause the cost-of-deployment to exceed acceptable thresholds, which renders the target Service-Area-of-Interest (SAOI) as being non-viable.

An alternative approach to augmenting CLOS design methodologies is to employ the use of diffraction to enable non line-of-sight (NLOS) links. These NLOS links exploit natural diffraction propagation effects that scatter the radio signal around a blocking obstacle, thus conveying signal energy into the shadow regime.

The main challenges in exploiting NLOS in terrestrial microwave backhaul networks has traditionally been in the following areas:

- Accurate prediction of the operation and performance of a NLOS radio link at high frequencies (i.e., 6 - 8 GHz)
- 2. Prediction of the over-life availability performance of NLOS radio links





Figure 1. High-level CLOS and NLOS opportunity space classification.

NLOS encompasses a wide range of physical situations, from Fresnel zone obstructions to single diffraction to multiple diffractions over different foliage levels. It can also include longer range links over water (which get obstructed due to the earth's curvature). Our first solution set, NLOS v1, provides a solution for:

- 1. High frequency terrestrial microwave backhaul in the 5.8 GHz 8 GHz range
 - a. 5.8 GHz as an unlicensed, high-power outdoor solution.
 - b. 6 8 GHz bands comprising various site-licensed Common Carrier radio bands which are employed internationally for highly directive Point-to-Point (PtP) microwave backhaul applications.
- 2. Single main diffracting obstacle in the radio path.
- 3. The main diffracting obstacle may be partially or fully blocking the first Fresnel zone.
- 4. The blocking obstacle may have moderate foliage coverage.
- 5. < 3 degrees diffraction angle is present in the radio path.





1.3 Use of NLOS in Network Design

When NLOS and CLOS are combined into a hybrid design approach, the use of NLOS can yield significant impact on network design and coverage. To understand this beneficial impact, Facebook undertook a number of design studies and investigations. In one sample case shown, the rural area in the proximity of the city of Jaén, Peru was investigated. Jaén is a larger settlement where there is fiber. However, the small rural settlements/areas around Jaén are largely un/under-connected and are located in the midst of somewhat challenging hilly, mountainous terrain. Sample network designs were undertaken to understand the impacts of exploiting NLOS terrestrial backhaul.



Figure 2. Example network design comparison using only CLOS links (left) and using a combination of CLOS and NLOS links (right). Green links are CLOS, magenta are diffracted NLOS. Red sites are repeater sites. Yellow sites are RAN sites.





When NLOS and LOS links are used together, a number of benefits are possible/evident:

- 1. Some of the links can be built using diffractive NLOS without needing repeaters.
- 2. Some RAN sites could be better positioned to provide better coverage.
- 3. Some sites may be deployed using shorter towers.

Overall, in this example we are able to achieve the same coverage goals with significantly reduced CAPEX and OPEX by using a hybrid combination of CLOS and NLOS in the network design.

1.4 Exploiting Diffractive NLOS Wireless Backhaul

It is known that when a signal impinges on an edge, some of its energy is bent into the geometric shadow of the obstacle. This phenomenon is called diffraction. Although this phenomenon is well-known in physics — see for example Sec 3.1 — it is rarely used in terrestrial mobile network backhaul applications because it is widely believed to be difficult to accurately predict its performance.

The main element that is impacted by diffraction is the overall path loss incurred in the radio link design. The path losses have to be overcome by the radio equipment's *system gain*, with additional link budget allocations for rain and multipath-induced fading. The path loss predictions typically are imputed with field margins to accommodate field and prediction uncertainties. In longer range CLOS radio links, this margin is typically ~ 3dB.

If diffraction could be predicted with improved reliability, it could be used to design and build wireless backhaul links in challenging environments, reducing the need to build repeaters and making network design more efficient.







NLOS adds an incremental path loss factor onto the radio path loss predictions, that of diffraction loss. As shown below, when the diffracting angle into the shadow area increases, so does the overall loss due to the increasing diffraction losses. The angle that the diffracted radio signal follows from the transmitter to the receiver in shadow area is known as the diffraction angle.







To assess the potential impact of diffractive NLOS links, Facebook conducted design studies based on realworld examples from rural Peru. In the example below, the hybrid uses of LOS and NLOS links could reduce the number of repeaters needed to provide connectivity in a given cluster of settlements.

To achieve this, we have made advances in experiments, physics modeling, and signal prediction. All this has improved the performance of prediction algorithms to reliably predict signal strength in diffraction and for network planning.

The workflow presented here has been used successfully by Internet para Todos (IpT) and Mayutel in the field. NLOS links designed and deployed by these partners are live and are part of their production network.





1.5 Proving and Deploying the Solution

The complete solution set that we developed included an end-to-end workflow for link design, network planning, and site deployment. To prove this solution, we worked with TeleworX, IpT de Peru and Mayutel to test this workflow in the real world, resulting in successful deployments in Peru.

IpT is a wholesale Network-as-a-Service operator in Peru, providing infrastructure to network operators. Founded in 2019, IpT has deployed hundreds of broadband sites in rural areas of Peru to date. IpT has successfully deployed dozens of NLOS links in their network, providing both end-point and backbone transport connectivity. The inclusion of NLOS has enabled IpT to efficiently expand their terrestrial network without making modifications to their infrastructure that would be necessary if only CLOS links were used.

Mayutel is Peru's first rural mobile infrastructure operator, providing broadband connectivity to many parts of rural Peru. Mayutel has deployed and tested a drone-based link validation workflow to better assess the performance of NLOS links.

Example Link #1



Figure 5. Terrain profile of NLOS link #1 that was deployed in Peru, produced using PathLoss5.0.







Figure 6. Terrain profile of NLOS link #2 that was deployed in Peru, produced using PathLoss5.0.

Example Link #3



Figure 7. Terrain profile of NLOS link #3 that was deployed in Peru, produced using PathLoss5.0.





Figure 8. Rural Peru deployment pictures from Mayutel.



2. Diffractive Microwave Links for NLOS Wireless Backhaul

In this section we present a workflow for including NLOS wireless backhaul links in an overall network design and deployment. This new NLOS workflow comprises several steps modified from conventional CLOS wireless backhaul workflow.

2.1 Backhaul Network and Link Design

- 1. Identification of the target Service Areas of Interest (SAoI)
 - a. Usually aligned with the locations of settlements in which the operator is intending to provide RAN coverage
 - b. In many cases, these sites are in/near the target SAoI locations
- 2. Identification of useful infrastructure elements in the deployment area
 - a. Existing tower sites
 - i. Allowed rad centers available
 - ii. Height vs. antenna size limitations (tower strength models)
 - b. Locations of roadways
 - c. Locations of other infrastructure which might be useful
 - i. Water towers, grain elevators, fire towers, etc.
 - d. Locations of any real estate assets which might be available for new-tower builds
- 3. Establish list of backhaul "design rules," to be accepted by the operator/partner
 - a. Operating parameters (frequency, channel size, min link capacity, target link availability, etc)
 - b. Max backhaul antenna sizes allowed
 - c. Max new-build radio tower heights allowed
 - d. List of maximum link distances allowed for a given antenna size, capacity, availability
 - i. For CLOS and NLOS backhaul links
- 4. Network link preliminary designs



- a. Using the CLOS "design rules," and Google Earth, determine a preliminary set of viable link paths able to achieve CLOS conditions
- b. Using the NLOS "design rules," and Google Earth, determine a preliminary set of viable links paths which are NLOS in nature
- c. Iterate 4a and 4b until an optimized network topology is achieved
- 5. Backhaul link design finalizations
 - a. Migrate the site and link information to PathLoss5.0
 - i. Build models for antennas, and radio equipment models
 - b. Use SRTM (Shuttle Radar Topography Mission) or other best available data for topo and terrain database
 - c. Add foliage as required (Google Earth can be used to gather tree-cluster information).
 - In areas with very dense foliage, SRTM topo databases may have distortions/errors caused by the foliage impacts on the SAR responses used in creating the SRTM databases. This also applies to building clutter in urban areas.
 - ii. Iterate link designs in PathLoss until a suitable backhaul network is derived
 - iii. For CLOS radio links: model with ITU-530 model. Apply 3 dB field margin. Employ International Telecommunications Union (ITU) rain region data with care taken to confirm with local rain statistics information (if available).
 - The outputs of this process are a link transmission analysis report which outlines all aspects of the radio link design, including the targeted [clear weather] receive signal levels (RSL) levels needed to support the link's availability performance (these are also used in the link's field alignment procedure, see below)
 - iv. For NLOS radio links: it is recommended to use paths with single diffracting obstacle only. Model with PathLoss5.0 native diffraction algorithm (which is a modified Longley Rice model) using radiused approximations
 - 1. The outputs of this process are a link transmission analysis report which outlines all aspects of the radio link design, including the targeted [clear





- 6. Confirmation of RAN coverage
 - a. Build models for the RAN equipment to be deployed
 - b. Establish the coverage propagation model to be used (i.e., Hata, 3GPPP, etc).
 - i. Including the acceptable Rx signal levels at the UE and base-station locations (cell edge conditions)
 - ii. Identify whether the RAN performance is uplink or downlink limited
 - c. Validate RAN performance in the network by building RAN models at the various RAN tower locations in order to confirm their respective coverage of the various SAOIs in the deployment area.
- 7. Iterate steps 5 and 6 until an optimized network design is achieved.





2.2 Radio Alignment

2.2.1 CLOS Radio Links -

radio system alignment

CLOS radio antenna alignment procedure is well-known and is based on simple geometric considerations.

In rural cases, towers are usually employed for the terrestrial radio network. The point-to-point (PtP) radio systems are manually aligned by tower climbers on both ends of the radio link, preferably in clear weather. During the iterative alignment procedure, the climbers on both ends typically use voice communication through long-range shortwave radios. In some cases the PtP system itself has a wayside call channel which allows the climbers to communicate once a coarse alignment has been achieved. The PtP radio antennas are iteratively pointed and fine-tuned in order to achieve the desired RSLs which support the targeted clear weather link margin values, to support the designed availability performance of the link.

On very long-haul links, extended visual measures are often employed to aid in the initial [coarse] alignment, such that the radio system can begin functioning. These measures may include:

- Night strobe lights
- Sun mirrors/reflectors
- Long range sight magnifiers (so called "gun sights")

2.2.2. NLOS Radio Links -

radio system alignment

Diffraction is a 3-dimensional phenomenon that depends on the diffracting feature. Therefore, both azimuthal and pitch adjustments into alignment consideration, based on the shape and geometry of the diffracting feature.





• Azimuthal angle adjustment: should compensate for the knife-edge facing angle

A diffracting path is determined by the angle of the diffracting feature. As shown in Figure 9, it is the *normal* to the slope of the feature.



Figure 9. An NLOS diffracting path based on the normal slope of the terrain and foliage.

On Figure 9 we show the top, side, and 3-D views of the NLOS radio alignment, showing the pitch and azimuthal adjustment that needs to be made to optimize the signal strength.



For NLOS radio links, installation technicians don't have the luxury of being able to use optical-eyesight techniques to facilitate the initial alignment step (to achieve coarse alignment of the PtP system antenna beams). The azimuthal alignment and approximate elevation-pointing area based on the link's simulation information which is employed for the initial (coarse) alignment. The initial alignment is done using compassing (azimuth pointing direction), combined with optical alignment to the crest of the diffracting (blocking) hilltop/obstacle.

Because of the 3-dimensional nature of the diffraction propagation mechanism, a successful coarse alignment may involve iterative adjustment of both the azimuthal and elevation pointing angles of the PtP system's antennas. In the majority of NLOS link cases, the optimized signal levels will be achieved on the direct path between the endpoints, it is possible that there may be more than one radio path which achieves acceptable signal levels. The climbers will need to iteratively optimize the alignment on more than one path in order to determine which of these is in fact the best path. Optimization takes the form of fine, iterative adjustments of the antenna pointing angles in order to achieve a maximized RSL level, along with good short term RSL stability.

A recent field example has shown that in most cases, aligning the radios toward the diffracting feature, following NLOS guidelines, yields much higher signal levels than if they were aligned directly at each other following CLOS guidelines.

On Figure 10 below we show the impact of improved NLOS signal alignment on NLOS link example #1, where the signal level was improved from -65dBm to -57dBm, matching the predicted signal level shown on Figure 11.





Figure 10. Comparison of traditional CLOS versus NLOS alignment, showing azimuthal and pitch adjustments and resulting signal values for Link #1.

Atmospheric absorption loss (dB)	0.02	
Net path loss (dB)	83.38	83.38
Receive signal (dBm)	-57.38	-57.38
Thermal fade margin (dB)	21.62	21.62
Worst month multipath availability (%)	100.00000	100.00000
Worst month multipath unavailability (sec)	0.00	0.00
Annual multipath availability (%)	100.00000	100.00000
Annual multipath unavailability (sec)	0.00	0.00
Annual 2 way multipath availability (%)	100.00000	
Annual 2 way multipath unavailability (sec)	0.00	
Polarization	Vertical	
0.01% rain rate (mm/hr)	47.89	
Flat fade margin - rain (dB)	21.62	
Rain attenuation (dB)	21.62	
Annual rain availability (%)	100.00000	
Annual rain unavailability (min)	0.00	
Annual rain + multipath availability (%)	100.00000	
Annual rain + multipath unavailability (min)	0.00	

Figure 11. PathLoss5.0. Prediction for example Link #1.



The result of the additional complexities and possible additional iterative steps can result in more time being required for NLOS link alignments (as compared to their CLOS counterparts).

Finally, we note that in some cases there may be several possible diffracting paths because of the shape of the obstacle. Therefore, the network designers and field engineers may be able to choose from several signal pathing options.



Figure 12. An alternative NLOS diffracting Radio Path around the obstacle.

2.3 Field validation of Radio Links

Before Deployment of Towers or PtP Radio Systems

The validation process for the following microwave backhaul link-types is considered for both CLOS and NLOS links.





2.3.1 CLOS Link Validation

The prediction methodology for CloS radio links has been established/validated and widely used for the better part of a century. The path losses associated with these links is therefore not usually subject to validation requirements. However, the prediction that a radio path is able to achieve Fresnel-clear LoS is a potential risk area requiring field validation before civil works are commenced. These link paths are usually validated using visual inspection by a field crew. Tower climbers are employed to verify that the link end sites can be seen from one another. Although this validation doesn't fully validate the Fresnel-clearance parametrics of the link's [paper] design, it provides a very high degree of confidence that the predictions are valid, and that there are no unforeseen obstacles in the radio path.

2.3.2 NLOS Link Validation

NLOS links are harder to validate because they have additional variables which contribute to performance risk:

- 1. Diffraction loss predictions have some degree of variability due to the specific nature of the diffracting earth's surface composition.
- 2. Diffraction loss predictions have some degree of variability due to foliage cover on/near the main diffracting feature in the radio path.
- 3. In other parts of the radio path, the assumption of Fresnel-clear operation requires validation in a similar way to that described in the previous sub-section.

The more typical deployment scenario involves a NLOS link path which is extended from an existing site. When the far-end tower site is not present, it is challenging to measure the path loss in order to confirm the link design predictions.





2.3.3 Drone-based validation

A drone can optionally be used to validate the link before civil works commence, by elevating an appropriate radio equipment and directional antenna. This allows for accurate emulation of the final deployment, to assess risk in complex situations, validate NLOS link prediction, and gather systematic data for further model improvements.



Figure 13. NLOS Link Field Validation Using the Drone

The drone can initially be flown at sufficient height to achieve clear LOS over the path obstruction. At this altitude, the far-end transmitter's high gain antenna is aligned for the correct receive signal level. The drone is then lowered whilst gathering receive signal levels as it descends, allowing a validation of the link at the target mounting height. In some cases, the drone may be flown in three dimensions in order to search for an optimized new-tower installation location and tower height.





3. Background Information

3.1 Diffraction Phenomena and Modeling

Diffraction is a well-known phenomenon in physics. Of particular importance is the knife-edge diffraction phenomenon, where a signal impinges upon a sharp edge or feature. When the feature is very sharp, then it is possible to predict how much signal energy is diffracted into the shadow zone using an analytical mathematical formula.

The diffraction phenomena is well-known in radio propagation modeling, for example see ITU recommendation ITU-R P.526-14. As such idealized knife-edge examples are not realistic in practice, empirical, and numerical formulas have been developed with the goal of providing reliable predictions.

The first major body of work to achieve this goal was the work of Anita Longley , Phil Rice, and their colleagues at what is now known as the Institute for Telecommunication Sciences. The output of her work is the well-known Longley-Rice model and the Irregular Terrain Model (ITM). This work is the basis of further improved models such as TIREM (Terrain Integrated Rough Earth Model) and PathLoss[™].

Unfortunately, there has been a lack of systematic experimentation addressing diffraction in the frequency bands of interest. This means that these models lack validation in relevant operating regimes and conditions. Lack of validation means that network designers do not use diffractive NLOS in carrier-grade network design.

To address this challenge, we developed a research program to gather systematic data, improve empirical models, and explore state-of-art physics-based modeling algorithms.





3.2 Diffractive NLOS Signal Modeling Research & Development

In our research program, we developed partnerships with university and industry experts. Universidad Politécnica de Madrid (UPM), The Ohio State University (OSU), Air Electronics, and Plexus Controls developed measurement instruments to measure signal propagation over difficult terrain and conducted systematic experiments in southern Ohio in the United States, in areas near Madrid in Spain, and in southern Ontario in Canada. University of Michigan (UM), George Mason University (GMU), OSU, and MIT developed propagation models, resulting in a number of publications and open-source software.



Figure 14. Experimental setups used by OSU and UPM.

Good signal prediction algorithms require good systematic data collection in a wide range of settings. To facilitate this, OSU, UPM, Air Electronics, and Plexus developed measurement instruments to measure signal propagation over difficult terrain. These instruments include those that could be mounted on drones to enable measurement at different heights and positions. OSU and UM worked on new advanced signal modeling algorithms. Facebook worked to improve proven empirical algorithms using new datasets. Facebook and GMU worked together on small- and large-scale assessments of the impact of this work on connectivity.





Figure 15. Example measurement profile and systematic data gathered in the field.

To facilitate knowledge sharing and collaboration, Facebook Connectivity organized a number of meetings, including at a Facebook-hosted workshop in 2019. The research and development work has yielded several publications that we list below. Further publications are expected in the near future.





4 List of Technical Publications

"Improving Rural Connectivity Coverage using Diffractive Non-Line of Sight (NLOS) Wireless Backhaul," World Wireless Research Forum (WWRF) 45, 2021.

Julius Kusuma; Erik Boch

Facebook Connectivity, USA

"Development of Measurement and Modeling Procedures of Diffractive near-LOS Wireless Links," Proceedings of the XXXIIIrd URSI General Assembly in Rome, 2020.

> José Manuel Riera (1); Santiago Pérez-Peña (1); Marta Castiella-Fernández (1); Pedro Velasco-de-la-Fuente (1); Mateo Burgos-García (1); Pedro Garcia-del-Pino (1); Luis Mendo (1); Julius Kusuma (2); Erik Boch (2)

(1) Universidad Politécnica de Madrid, Spain; (2) Facebook Connectivity, USA

- "itmlogic: The Irregular Terrain Model by Longley and Rice," The Journal of Open Source Software, 2020. Edward J Oughton (1, 2), Tom Russell (1), Joel Johnson (3), Caglar Yardim (3), and Julius Kusuma (4)
 (1) Environmental Change Institute, University of Oxford (2) Computer Laboratory, University of Cambridge (3) ElectroScience Laboratory, The Ohio State University (4) Facebook Connectivity Lab, Facebook Research
- "Hybrid Parabolic Equation Integral Equation Solvers for Analyzing Long Range Propagation Over Complex Terrain," IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI), 2019

Eric Michielssen (1), Max Bright (1), Julius Kusuma (2)

- (1) University of Michigan at Ann Arbor, (2) Facebook Connectivity
- "Gabor Frame-Based Sparsification and Radiation Boundary Conditions for Parabolic Wave Equations," IEEE

International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-

S/URSI), 2019 Max Bright (1), Eric Michielssen (1), Julius Kusuma (2)

(1) University of Michigan at Ann Arbor, (2) Facebook Connectivity

"Lower Atmospheric Propagation (LATPROP) Drone System", ESL CERF Meeting 2019, Aug. 6th, 2019, Columbus, OH L.

Xu, C. Yardim, S. Mukherjee and J. T. Johnson

The Ohio State University





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