Improving Rural Connectivity Coverage using Diffractive Non-Line of Sight (NLOS) Wireless Backhaul

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***Abstract*— Today, the design of microwave backhaul relies on Clear Line of Sight (CLOS) requirements. Unfortunately, for rural areas, lack of LOS between settlements means that a repeater or reflector has to be built, which leads to cost constraints. To address this challenge, we explore the use of diffraction, a physics phenomenon through which some wireless signal energy is bent into the geometric shadow of the obstacle. We show that when diffraction could be predicted reliably, it could be used to design and build wireless Non- Line of Sight (NLOS) backhaul links in challenging environments, reducing the need to build repeaters and making network design more efficient. We present a feasible condition for the use of diffractive NLOS, for a single obstacle with shallow diffraction angle, modest foliage loss, and moderate foliage, which we call NLOSv1. This solution can be implemented using standard microwave backhaul radio and link design / network planning software. Through a design-study example, we show there is significant beneficial contribution to network design and implementation in rural/deep-rural networks. This solution has been implemented by Internet para Todos (IpT) and Mayutel in commercial, carrier-grade networks in Peru.**

Keywords—wireless; microwave; backhaul; rural; diffraction; line-of-sight; NLOS; propagation; pathloss

I. Introduction

Many rural/deep-rural areas around the world still don't have access to mobile connectivity, and technology innovations are needed. An important element of rural connectivity is backhaul, the links that connect remote sites to the core network of the internet. Wireless backhaul using microwave radio provides low cost and fast deployment compared to other options [1].

One major challenge in the deployment of wireless backhaul is lack of Line of Sight. Today, the design of microwave backhaul relies on Clear Line of Sight (CLOS) requirements. Unfortunately, for rural areas, lack of LOS between settlements means that a repeater or reflector has to be built, which leads to cost constraints. To address this challenge, we explore the use of diffraction, a physics phenomenon through which some wireless signal energy is bent into the geometric shadow of the obstacle. If diffraction could be predicted reliably, it could be used to design and build wireless Non- Line of Sight (NLOS) backhaul links in challenging environments, reducing the need to build repeaters and making network design more efficient [2,3].

II. Diffractive NLOS Wireless Backhaul

A. Diffraction Modeling for Radio Propagation

The diffraction phenomenon is well-known in radio propagation modeling. It is known that diffraction conveys signal energy into the shadow NLOS regime, as shown in Figure 1, and that if it could be predicted reliably, it could be used for wireless communication. 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 address 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) [4]. This work is the basis of further improved models such as TIREM (Terrain Integrated Rough Earth Model) and PathLoss™. Such empirical models combine idealized knife-edge formulas with geometric corrections to account for exact shapes, foliage, and other factors. These empirical models are the most-used models in

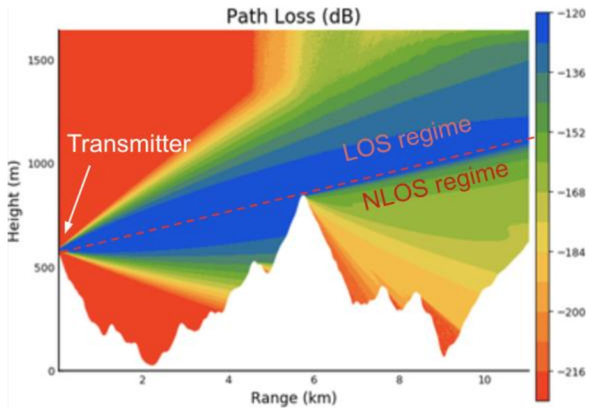

Figure 1. Diffracted propagation modeling result [9,10].

practice, having been implemented in commercial microwave backhaul design software packages such as PathLoss™ [5,6,7].

Other approaches to diffraction modeling have been developed, using high-frequency approximation and numerical methods. This includes ray-tracing algorithms, Parabolic Equations (PE) and Integral Equation (IE). See for example [8] for a thorough review of the domain. More recently, hybrid methods that combine PE and IE have been developed to address challenges such as input data uncertainty, foliage, and buildings [9,10].

Given the popularity of (semi-)empirical algorithms among network designers, we focus on these commercially available algorithms and software packages. More specifically, to maximize adoption among carrier-grade wireless backhaul and network designers, we use the widely-used software package *PathLoss5.0* ™ as the reference software and algorithm, and focus on solutions that can be implemented using standard carrier-grade wireless backhaul radio equipment.

B. Systematic Experiments for Diffraction Modeling

In spite of many publications addressing propagation modeling, 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 tend to avoid the 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.

In our research program, we developed partnerships with university and industry experts, including Universidad Politécnica de Madrid (UPM), The Ohio State University (OSU), Air Electronics, and Plexus Controls. We 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.

In the work reported here, we leverage field measurements undertaken by UPM in a number of sites near Madrid [11]. The test sites were selected to provide suitable diffraction conditions. One of the main factors was to identify sites which provide a shallow diffraction angle across a single primary geographic feature. The locations of the sites are given in Table I and Fig. 2.

Site Name	LAT	LONG
D 0624 Montala - Site A	40 22 30.4 N	4 15 30.5 W
D 0624 Montala - Site B	40 22 33.0 N	4 23 45.8 W
D 0627 Montala - Site A	40 24 26.0 N	4 30 08.9 W
D 0627 Montala - Site B	40 22 30.4 N	4 15 30.5 W
D 0702 Montala - Site A	39 44 59.9 N	4 11 57.7 W
D 0702 Montala - Site B	39 41 08.7 N	3 43 59.8 W
D 0705 Montala - Site A	39 44 59.9 N	4 11 57.7 W
D 0705 Montala - Site B	39 41 45.6 N	3 44 34.2 W
D 0717 Montala - Site A	40 27 12.6 N	3 43 36.0 W
D 0717 Montala - Site B	40 27 57.3 N	4 29 03.5 W

Table I. List of measurement sites from [11].

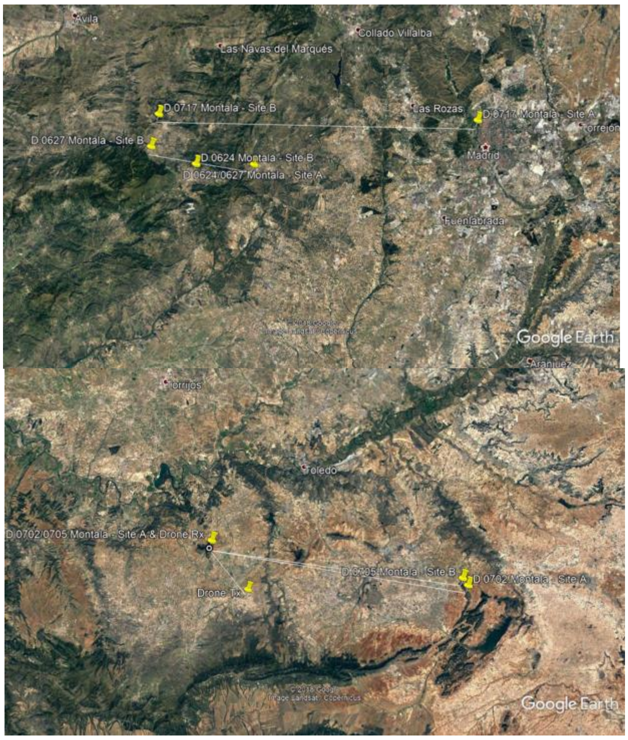

Figure 2. Locations of test sites near Madrid, Spain.

C. PathLoss5.0 Model Validation

Based on the results of this measurement, experimental, and modeling campaign, we have determined the feasibility of diffractive NLOS for the first use-case, which we call NLOSv1:

1. Native "PathLoss" model, based on the classic Longley-Rice/Reasoner algorithm.
2. TIREM model, based on the US Army TIREM algorithm.

In both cases rounded knife-edge feature modelling was employed. Where foliage was modelled, it was modelled as foliage placed in the vicinity of the primary diffracting location on the radio path, using dry, mixed forest model, with continental temperate climate conditions. A sample of the predictive results from *PathLoss5.0* are shown in Fig. 3.

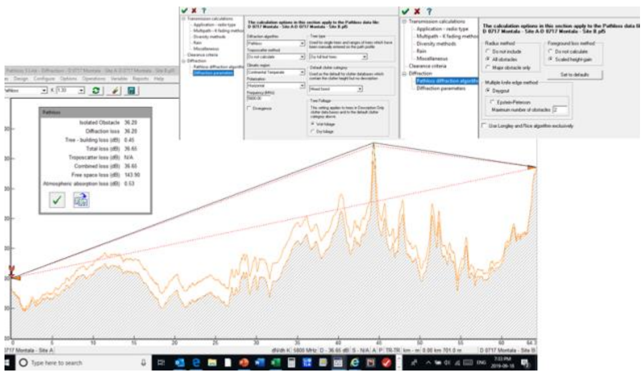

Figure 3. Example *PathLoss5.0* setup and output.

SITE A Name	SITE A LAT	SITE A LONG	SITE A Ant H (m AGL)	SITE B Name	SITE B LAT	SITE B LONG	SITE B Ant H (m AGL)	Link Range (km)	Freq (GHz)	Measured Diffraction loss V	PathLoss5.0 (native Longley/Rice/Reasoner) no foliage V	error (dB) V	with foliage V	error (dB) V	PathLoss5.0 (TIREM) no foliage V	error (dB) V	with foliage V	error (dB) V
D 0624 Montala - Site A	40 22 30.4 N	4 15 30.5 W	2	D 0624 Montala - Site B	40 22 33.0 N	4 23 45.8 W	2	11.7	5.8	29.6	30.9	1.3	32.8	3.2	26.5	-3.0	28.4	-1.2
D 0627 Montala - Site A	40 24 26.0 N	4 30 08.9 W	2	D 0627 Montala - Site B	40 22 30.4 N	4 15 30.5 W	2	21	5.8	44.0	38.2	-5.8	39.0	-5.0	39.0	-5.0	39.8	-4.3
D 0702 Montala - Site A	39 44 59.9 N	4 11 57.7 W	2	D 0702 Montala - Site B	39 41 08.7 N	3 43 59.8 W	2	40.6	5.8	22.6	24.8	2.2	26.3	3.7	23.2	0.6	25.0	2.4
D 0705 Montala - Site A	39 44 59.9 N	4 11 57.7 W	2	D 0705 Montala - Site B	39 41 45.6 N	3 44 34.2 W	2	39.6	5.8	33.4	35.5	2.1	36.1	2.8	31.4	-2.0	32.0	-1.3
D 0717 Montala - Site A	40 27 12.6 N	3 43 36.0 W	35	D 0717 Montala - Site B	40 27 57.3 N	4 29 03.5 W	2	64.3	5.8	29.7	36.9	7.2	36.7	6.9	33.8	4.1	34.3	4.5
									Averages	31.9	33.3		34.2		30.8		31.9	

Table II. Mast-to-mast data and analysis

SITE A (Mast) Name	LAT	LONG	Ant H (m AGL)	SITE B (Drone) Name	LAT	LONG	Ant H (m AGL)	Freq (GHz)	Measured Diffraction loss V	Longley/Rice/Reasoner without foliage V	error (dB) V	with dry foliage V	error (dB) V	TIREM without foliage V	error (dB) V	with dry foliage V	error (dB) V
Mast RX	39 44 59.9 N	4 11 57.7 W	2	Drone Tx	39 40 57.19 N	4 07 59.36 W	80.4	5.8	27.5	17.8	-9.7	23.0	-4.5	16.5	-10.9	21.7	-5.7
Mast RX	39 44 59.9 N	4 11 57.7 W	2	Drone Tx	39 40 57.19 N	4 07 59.36 W	69.3	5.8	30.6	21.6	-9.0	25.6	-5.0	19.9	-10.7	23.8	-6.8
Mast RX	39 44 59.9 N	4 11 57.7 W	2	Drone Tx	39 40 57.19 N	4 07 59.36 W	59.4	5.8	31.3	24.6	-6.7	27.8	-3.6	22.7	-8.6	25.5	-5.8
Mast RX	39 44 59.9 N	4 11 57.7 W	2	Drone Tx	39 40 57.19 N	4 07 59.36 W	50.3	5.8	31.0	27.1	-3.9	29.7	-1.3	24.4	-6.6	27.0	-4.0
Mast RX	39 44 59.9 N	4 11 57.7 W	2	Drone Tx	39 40 57.19 N	4 07 59.36 W	40.7	5.8	31.5	29.0	-2.5	31.4	-0.1	26.0	-5.5	28.2	-3.3
Mast RX	39 44 59.9 N	4 11 57.7 W	2	Drone Tx	39 40 57.19 N	4 07 59.36 W	30.1	5.8	30.3	31.1	0.8	33.0	2.8	27.3	-2.9	29.2	-1.0
Mast RX	39 44 59.9 N	4 11 57.7 W	2	Drone Tx	39 40 57.19 N	4 07 59.36 W	20.9	5.8	35.5	32.8	-2.7	34.5	-1.0	28.5	-7.0	30.2	-5.3
Mast RX	39 44 59.9 N	4 11 57.7 W	2	Drone Tx	39 40 57.19 N	4 07 59.36 W	14.1	5.8	30.1	33.7	3.6	33.3	3.2	29.1	-1.0	30.7	0.6
								Averages	31.0	27.2	-3.8	29.8	-1.2	24.3	-6.7	27.1	-3.9

Table III. Mast-to-drone data and analysis

We analyzed two sets of measurements. The first set was taken from mast-to-mast, given in Table II. The second set was taken from a mast to a drone-mounted receiver, called mast-to-drone, given in Table III.

1) Mast-to-mast data and analysis

We found that *PathLoss5.0* predictions were consistent with previous comparative analysis, suggesting estimation errors under 6dB for Longley/Rice, and under 4dB for TIREM. Inclusion of foliage provides a slight reduction in prediction errors.

From the Table II, it can be seen that across the various field test links which have shallow diffraction angles, the diffraction losses are reasonably consistent, in the range of 25-35dB. This is an important parametric observation which is discussed further in a later section of this document.

2) Mast-to-drone data and analysis

The use of a drone allowed UPM to take systematic, densely spaced measurements at various heights and angles, in the same locations. More specifically, this setup more closely resembles the geometries used in rural connectivity where wireless backhaul antennas are mounted on towers at heights of 10-50m [2,3].

On Table III and Fig. 4 we show the diffraction loss prediction error of various models as applied to mast-to-drone data, based on foliage conditions and heights Above Ground Level (AGL). The shaded area of Fig. 4 represents the region of interest for rural/deep-rural terrestrial microwave backhaul deployments, where reasonable (cost-effective) tower heights are generally < 50m in height. In this area the prediction errors are within ~6dB, consistent with the mast-to-mast data set.

D. Feasibility of Diffractive NLOS Wireless Backhaul

The results of this measurement, experimental, and modeling campaign are used to establish the feasibility of diffractive NLOS for the first use-case, which we call NLOSv1:

1. High frequency terrestrial microwave backhaul in the 5.8GHz - 8GHz range

    a. 5.8GHz as an unlicensed, high power outdoor solution.

    b. 6 - 8GHz bands comprising various site-licensed Common Carrier radio bands which are employed internationally for highly directive Point-to-Point (PtP) microwave backhaul applications.

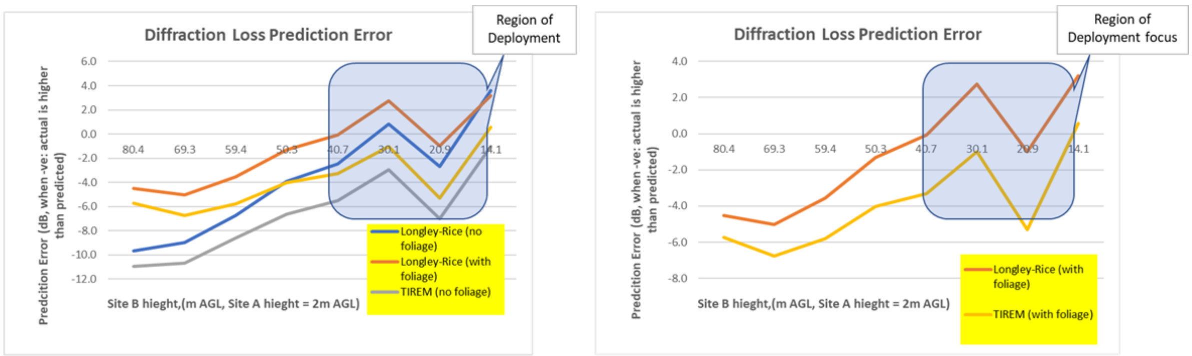

Figure 4. Mast-to-drone data and analysis

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.

Putting this into commercial wireless backhaul context, we established the feasibility of the following:

- 20km link with up to 3-deg diffraction angle, 100Mbps/QPSK.@ 99.8% availability, and an ability to deliver 525Mbps full duplex (continuous) @ > 98%
- 11km link with up to 3-deg diffraction angle, 100Mbps/QPSK @ 99.99% availability, and an ability to deliver 525Mbps full duplex (continuous) @ > 99.9%

To turn this feasibility into practice, we have developed a design-and-deployment workflow for NLOSv1 links, validated by our partners Internet para Todos (IpT) and Mayutel in Peru. This workflow is shared and presented in the Network-as-a-Service (NaaS) Solution project group of the Telecom Infra Project [12].

III. Impact of NLOSv1 on Rural Network Design

With the feasibility of NLOSv1 established and proven – both in experiments and real-life production-grade networks – we can now assess the impact of NLOSv1 on network design and rural connectivity coverage potential. When NLOS and CLOS are combined together into a hybrid design approach, the use of NLOS can yield significant impact on network design and coverage.

A. *Case study of NLOSv1 based on a cluster near Jaén, Peru*

To assess the impact of NLOSv1 on rural network design, we undertook a number of design studies & investigations. In one sample case shown here, we assess the cluster-level impact of NLOSv1 on the rural area in the proximity of the city of Jaén Peru was investigated. Jaén is a larger settlement with fiber access. 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, as shown on Fig. 5.

When only CLOS backhaul links are used, two repeater sites (shown in red) are required to provide signal paths in rugged parts of the cluster. Further, to provide sufficient RAN coverage and backhaul clearance, 7 of the RAN towers have to be built taller, further adding to costs.

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.

In this example, to achieve the same coverage goals, the CAPEX and OPEX are reduced significantly when using a hybrid combination of CLOS and NLOS in the network design.

B. *Deployment of NLOSv1 in production networks in Peru*

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 Internet para Todos (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 many hundreds of broadband sites in rural areas of Peru. Through the hybrid combination of CLOS & NLOS backhaul radio links, IpT has been able to optimize the network design to increase the coverage of the network, whilst simultaneously reducing deployment costs significantly.

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.

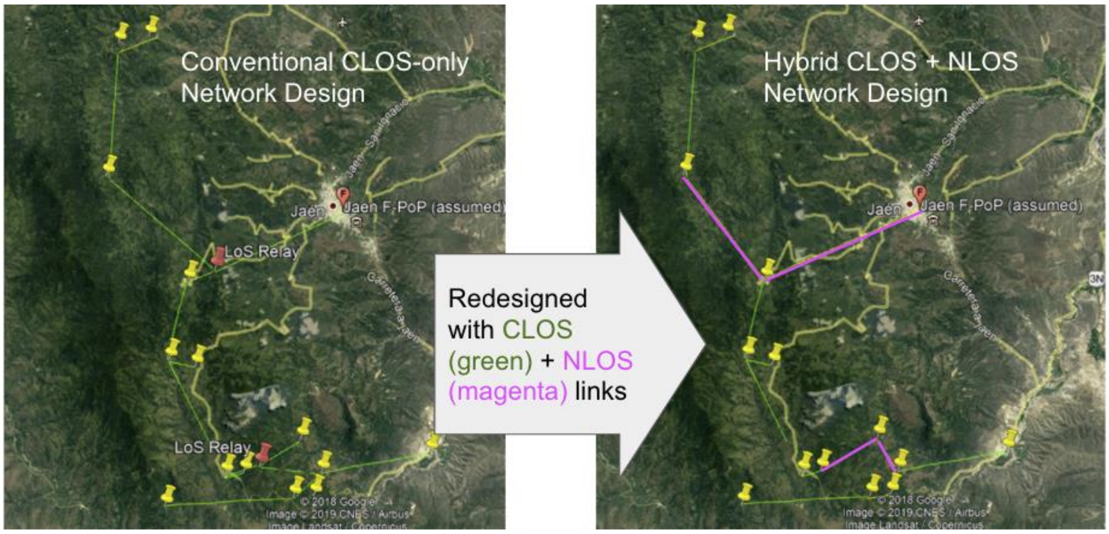

Figure 5. A design case study based on a cluster around Jaén, Peru, showcasing the benefits of CLOS+NLOS design: no repeaters are needed, better RAN site positioning & coverage, site cost reductions by using shorter towers closer to roads.

IV. Closing Remarks

The work reported herein is focused on simple, single diffraction use-case scenarios. Using available modelling methods, field results from a number of obstructed radio paths have been used to assess modelling accuracy and determine suitable link budget margins needed for reliable wireless-backhaul-link predictive-modelling. The use of diffractive NLOS wireless backhaul links in combination with CLOS radio links provides significant cost-performance benefits to rural & deep-rural networks, particularly in areas where terrain is challenging.

Even with NLOSv1 – based on a modest feasible regime and conservative link margins – there are significant gains in coverage & cost while satisfying carrier-grade performance requirements. Most importantly, operator-partners have adopted and implemented this solution in their carrier-grade production networks.

Further experimental and modeling efforts can bring significant further benefits, including to the reduction of link budget margins, improve the modelling of foliage, weather and seasonal elements, as well to increase the feasibility-space to include more complex obstacles and regimes.

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