Ericsson Review

The communications technology journal since 1924

2013 • 3

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February 22, 2013

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Non-line-of-sight microwave backhaul for small cells

The evolution to denser radio-access networks with small cells in cluttered urban environments has introduced new challenges for microwave backhaul. A direct line of sight does not always exist between nodes, and this creates a need for near- and non-line-of-sight microwave backhaul.

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Using non-line-of-sight (NLOS) propagation is a proven approach when it comes to building RANs However, deploying high-performance microwave backhaul in places where there is no direct line of sight brings new challenges for network architects. The traditional belief in the telecom industry is that sub-6GHz bands are required to ensure performance for such environments. This article puts that belief to the test, providing general principles, key system parameters and simple engineering guidelines for deploying microwave backhaul using frequency bands above 20GHz. Trials demonstrate that such high-frequency systems can outperform those using sub-6GHz bands – even in locations with no direct line of sight.

Point-to-point microwave is a cost-efficient technology for flexible and rapid backhaul deployment in most locations. It is the dominant backhaul medium for mobile networks, and is expected to maintain this position as mobile broadband evolves; with microwave technology that is capable of providing backhaul capacity of the order of several gigabits-per-second[1].

Complementing the macro-cell layer by adding small cells to the RAN introduces new challenges for backhaul. Small-cell outdoor sites tend to be mounted 3-6m above ground level on street fixtures and building facades, with an inter-site distance of 50-300m. As a large number of small cells are necessary to support a superior and uniform user experience across the RAN[2], small-cell backhaul solutions need to be more cost-effective, scalable, and easy to install than traditional macro backhaul technologies. Well-known backhaul technologies such as spectral-efficient LOS microwave, fiber and copper are being tailored to meet this need. However, owing to their position below roof height, a substantial number of small cells in urban settings do not have access to a wired backhaul, or clear line of sight to either a macro cell or a remote fiber backhaul point of presence.

The challenges posed by locations without a clear line of sight are not new to microwave-backhaul engineers, who use several established methods to overcome them. In mountainous terrain, for example, passive reflectors and repeaters are sometimes deployed. However, this approach is less desirable for cost-sensitive small-cell backhaul, as it increases the number of sites. In urban areas, daisy chaining is often used to reach sites in tricky locations – a solution that is also effective for small-cell backhaul (see **Figure 1**).

Network architects aim to dimension backhaul networks to support peak cell-capacity[3] – which today can reach 100Mbps and above. However, in reality, there is a trade-off among cost, capacity and coverage resulting in a backhaul solution that, at a minimum, can support expected busy-hour traffic with enough margin to account for statistical variation and future growth: in practice around 50Mbps with availability requirements typically relaxed to 99-99.9 percent. Such availability levels require fade margins of the order of just a few decibels for short-link distances.

For small-cell backhaul simplicity and licensing cost are important issues. Light licensing or technology-neutral block licensing are attractive alternatives to other approaches such as link licensing, as they provide flexibility[4]. Using unlicensed frequency bands can be a tempting option, but may result in unpredictable interference and degraded network performance. The risk associated with unlicensed use of the 57-64GHz band is lower than that associated with the 5.8GHz band, owing to higher atmospheric attenuation, sparse initial deployment, and the possibility of using compact antennas with narrow beams, which effectively reduces interference.

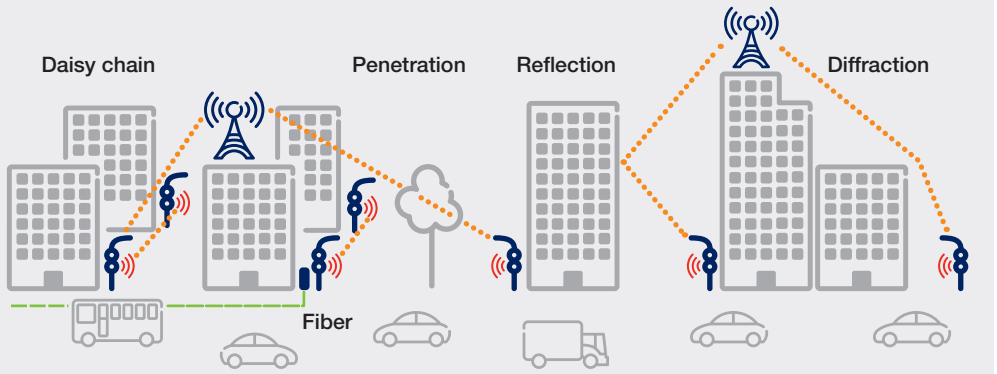
Providing coverage in locations without a clear line of sight is a familiar part of the daily life of mobile-broadband and Wi-Fi networks. However, maybe because such locations are commonplace, a number of widespread myths and misunderstandings surrounding NLOS microwave backhaul exist – for example, that NLOS microwave backhaul needs sub-6GHz frequencies, wide-beam antennas and OFDM-based radio

BOX A Terms and abbreviations

FDD	frequency division duplexing	NLOS	non-line-of-sight
LOS	line-of-sight	OFDM	orthogonal frequency division multiplexing
MIMO	multiple-input, multiple-output	RAN	radio-access network
		TDD	time division duplexing

technologies to meet coverage and capacity requirements. Despite this, a number of studies on NLOS transmission using frequency bands above 6GHz, for example, have been carried out for fixed wireless access[5] and for mobile access[6]. Coldrey et al. showed that it is realistic to reach 90 percent of the sites in a small-cell backhaul deployment with a throughput greater than 100Mbps using a paired 50MHz channel at 24GHz[7].

FIGURE 1 **Microwave backhaul scenarios for small-cell deployment**



NLOS principles

As illustrated in Figure 1, all NLOS propagation scenarios make use of one or more of the following effects:

- diffraction;
- reflection; and
- penetration.

All waves change when they encounter an obstacle. When an electromagnetic wave hits the edge of a building, diffraction occurs – a phenomenon often described as the bending of the signal. In reality, the energy of the wave is scattered in the plane perpendicular to the edge of the building. The energy loss – which can be considerable – is proportional to both the sharpness of the bend and the frequency of the wave[8].

Reflection, and in particular random multipath reflection, is a phenomenon that is essential for mobile broadband using wide-beam antennas. Single-path reflection using narrow-beam antennas is, however, more difficult to engineer owing to the need to find an object that can provide the necessary angle of incidence to propagate as desired.

Penetration occurs when radio waves pass through an object that completely or partially blocks the line of sight. It is a common belief that path loss resulting from penetration is highly dependent on frequency, which in turn rules out the use of this effect at higher frequencies. However, studies have shown that in reality path loss due to penetration is only slightly dependent on frequency, and that in fact it is the type and thickness of the object itself that creates the impact on throughput[9,10]. For example, thin, non-metallic objects – such as sparse foliage (as shown in Figure 1) – add a relatively small path loss, even for high frequencies.

Deployment guidelines can be defined given a correct understanding and application of these three propagation effects, giving network engineers simple rules to estimate performance for any scenario.

System properties

A simplified NLOS link budget can be obtained by adding an NLOS path attenuation term (ΔL_{NLOS}) to the traditional LOS link budget, as shown in Equation 1.

Equation 1

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - 92 - 20\log(d) - 20\log(f) - L_F - \Delta L_{NLOS}$$

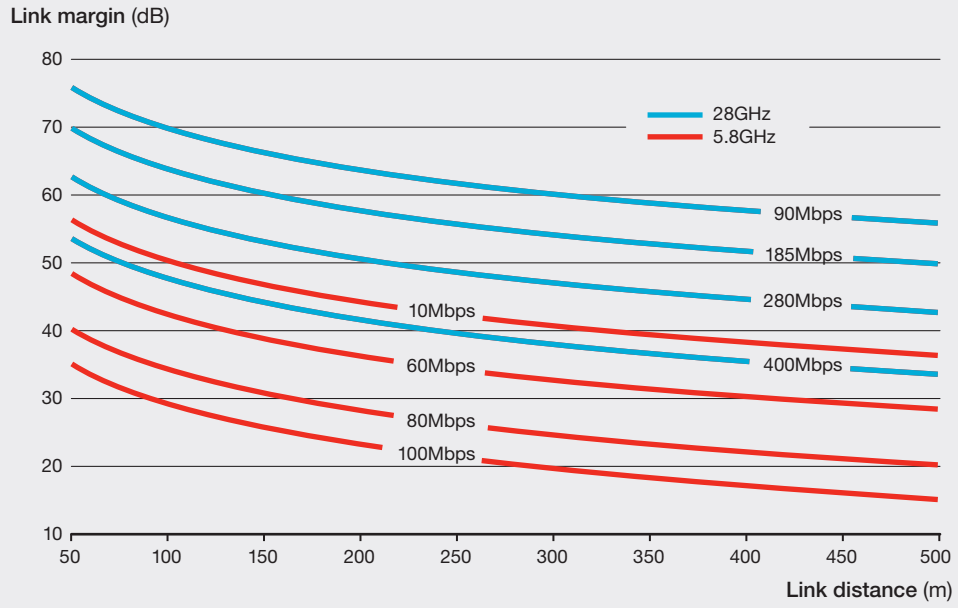
Here, P_{RX} and P_{TX} are the received and transmitted power (dBm – ratio of power in decibels to 1 milliwatt); G_{TX} and G_{RX} are antenna gain (in decibels isotropic – dBi) for the transmitter and receiver respectively; d is the link distance (in kilometers); f is the frequency (in gigahertz); L_F is any fading loss (in decibels); and ΔL_{NLOS} is the additional loss (in decibels) resulting from the deployment of NLOS-propagation effects. Not shown in this equation is the theoretical frequency dependency of the antenna gain, which for a fixed antenna size will increase as 20log(f) and as a consequence, the received signal – P_{RX} – will actually increase as 20log(f) when carrier frequency is increased for a fixed antenna size. This relationship indicates the advantage of using higher frequencies for applications where a small antenna form factor is of importance – as is the case for small-cell backhaul.

To determine the importance of NLOS-system properties, Ericsson carried out measurement tests on two commercially available microwave backhaul systems in different frequency bands (described in **Table 1**). The first system used the unlicensed 5.8GHz band with a typical link configuration for applications in this band. The air interface used up to 64QAM modulation in a 40MHz-wide TDD channel with a 2x2 MIMO (cross-polarized) configuration providing full duplex peak throughput of 100Mbps (200Mbps aggregate). The second system, a MINI-LINK PT2010, used a typical configuration for the licensed 28GHz band, based on FDD, 56MHz channel spacing and single-carrier technology with up to 512QAM modulation, providing full duplex throughput of 400Mbps (800Mbps aggregate). To adjust the throughput based on the quality of the received signal, both

Table 1: Test system specifications

SYSTEM	TECHNOLOGY	CHANNEL SPACING	ANTENNA GAIN	OUTPUT POWER	PEAK THROUGHPUT
5.8GHz	TDD/OFDM 64QAM	40MHz	17dBi	19dBm	100Mbps
28GHz	FDD/single carrier 512QAM	56MHz	38dBi	19dBm	400Mbps

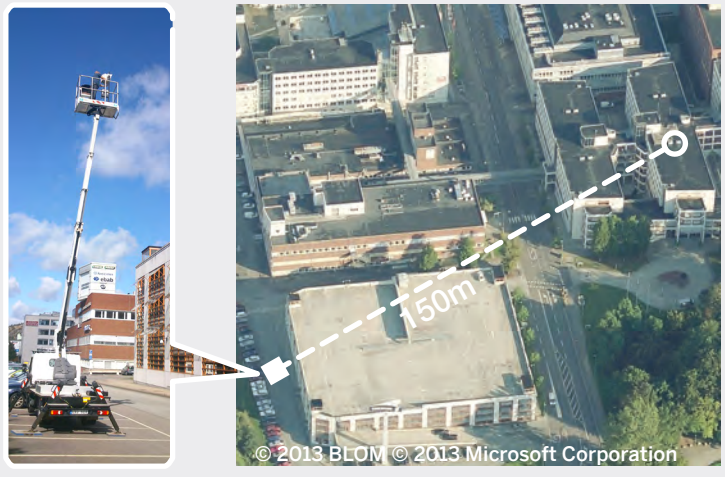
FIGURE 2 **Link margin as a function of throughput and distance**



systems used adaptive modulation. Physical antenna sizes were similar, but due to the frequency dependency of the antenna gain and the parabolic type used in the 28GHz system, it offered a gain of 38dBi while the flat antenna of the 5.8GHz system reached 17dBi.

Link margin versus throughput and hop distance is shown in **Figure 2**. Here, the margin is defined as the difference between received power (according to Equation 1) and the receiver threshold for a particular modulation level (throughput) – in line of sight conditions without fading ($L_f = 0$). If ΔL_{NLOS} caused by any NLOS effect can be predicted, the curves in Figure 2 can be used to estimate throughput. The advantages of using higher frequencies are clear: with comparable antenna sizes, the link margin is about 20dB higher at a peak rate of 400Mbps for the 28GHz system compared with the 5.8GHz system at a peak rate of 100Mbps.

FIGURE 3A **Test site for NLOS backhaul – diffraction**



Measurements

Diffraction

It is commonly believed that the diffraction losses occurring at frequencies above 6GHz are prohibitively high, and consequently, deploying a system using this effect for NLOS propagation at such frequencies is not feasible. However, even if the absolute loss can be relatively high, 40dB and 34dB for the 28GHz and 5.8GHz systems respectively (with a diffraction angle of 30 degrees), the relative difference is only 6dB[8] – much less than the difference in gain for comparable antenna sizes even when taking into account the higher free-space loss for the 28GHz system (see Figure 2).

Figures 3A and **3B** show the set-up and measured results of a scenario designed to test diffraction. A first radio was positioned on the roof of an office building (marked in Figure 3A with a white circle). A second radio was mounted on a mobile lift, placed 11m behind a 13m-high parking garage. The effect on the signal power received by the second radio was measured by lowering the mobile lift. Figure 3B shows the measured received signal-power versus distance below the line of sight for both test systems, as well as the theoretical received power calculated using the ideal knife-edge model[8]. Both radios transmitted 19dBm output power, but due to the 21dBi lower antenna gain for the 5.8GHz system, the received signal for this radio was 20dB weaker after NLOS propagation than the 28GHz system.

The measured results compare well against the results based on the theoretical model, although an offset of a couple of decibels is experienced by the 28GHz system – a small deviation that is expected due to the simplicity of the model.

To summarize, diffraction losses can be estimated using the knife-edge model[8]. However, due to the model's simplicity, losses calculated by it are slightly underestimated. This can be compensated for in the planning process by simply adding a few extra decibels to the loss margin.

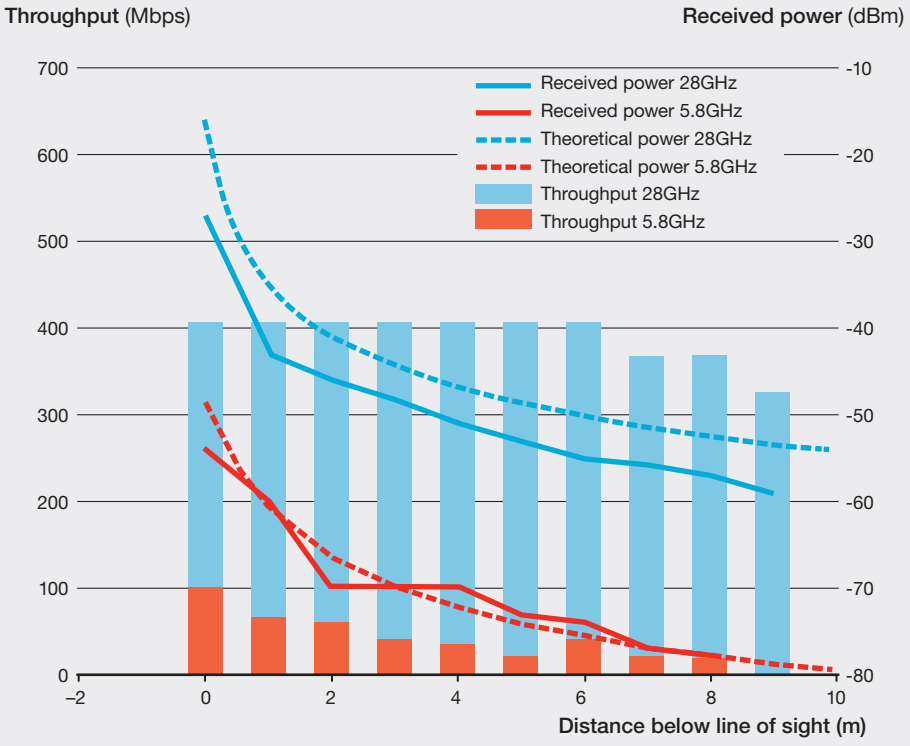
The 28GHz system can sustain full throughput at much deeper NLOS than the 5.8GHz system, which is to be expected as it has a higher link margin. Full throughput – 400Mbps – was achieved at 28GHz up to 6m below the line of sight, equivalent to a 30-degree diffraction angle, while the 5.8GHz system dropped to under 50Mbps at 3m below the line of sight. The link margin is the single most important system parameter for NLOS propagation and, as expected, the 28GHz system performs in reality better in a diffraction scenario than a 5.8GHz system with comparable antenna size.

Reflection

The performance characteristics of the 5.8GHz and 28GHz systems were measured in a single-reflection scenario in an area dominated by metal and brick facades – shown in **Figure 4A**. The first radio was located on the roof of the office building (marked with a white circle), 18m above ground level; and the second on the wall of the same building, 5m above ground, facing the street canyon. The brick facade of the building on the other side of the street from the second radio was used as the reflecting object, resulting in a total path length of about 100m. The reflection loss will vary with the angle of incidence, which in this case was approximately 15 degrees, resulting in a ΔL_{NLOS} of 24dB for the 28GHz system and 16dB for the 5.8GHz system – figures that are in line with earlier studies[11]. Reflection loss is strongly dependent on the material of the reflecting object, and for comparison purposes ΔL_{NLOS} for a neighboring metal facade was measured to be about 5dB for both systems with similar angle of incidence.

To summarize, it is possible to cover areas that are difficult to reach using multiple reflections in principle. However, taking advantage of more than two reflections is in practice problematic – due to limited link margins and the difficulty of finding suitably aligned reflection surfaces. ΔL_{NLOS} predictions for a single-facade reflection in the measured area can be expected to vary between 5dB and 25dB at 28GHz and between 5dB and 20dB at 5.8GHz. The throughput for both systems measured over 16 hours is shown in **Figure 4B**.

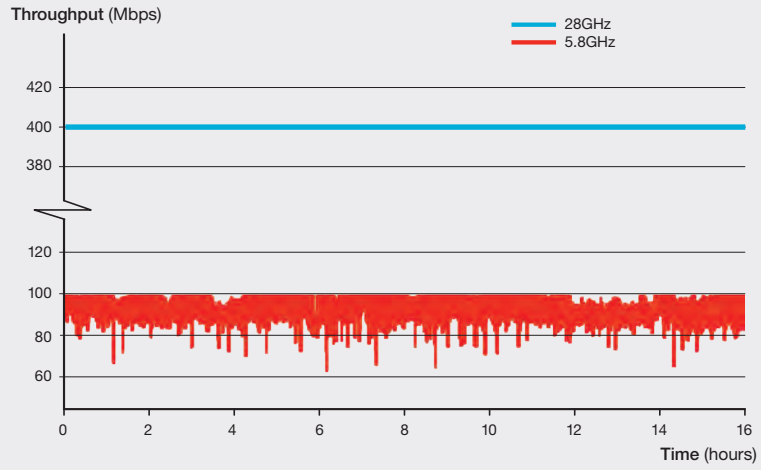
FIGURE 3B Throughput and received power – diffraction



The 28GHz system shows a stable throughput of 400Mbps, while the throughput for the 5.8GHz system, with a much wider antenna beam, dropped from 100Mbps to below 70Mbps. These variations are to be expected owing to the fact that the wider beam experiences a stronger multipath. OFDM is an effective mitigation technology that combats fading, which will, at severe multipath fading, result in a graceful degradation of throughput – as illustrated. However, the narrow antenna lobe at 28GHz, in combination with the advanced equalizer of the high-performance MINI-LINK radio, effectively suppresses any multipath degradation, enabling the use of a single-carrier QAM technology for NLOS conditions – even up to 512QAM and 56MHz channel bandwidths.

FIGURE 4A Test site for NLOS backhaul – reflection

FIGURE 4B **Throughput over time – single reflection**



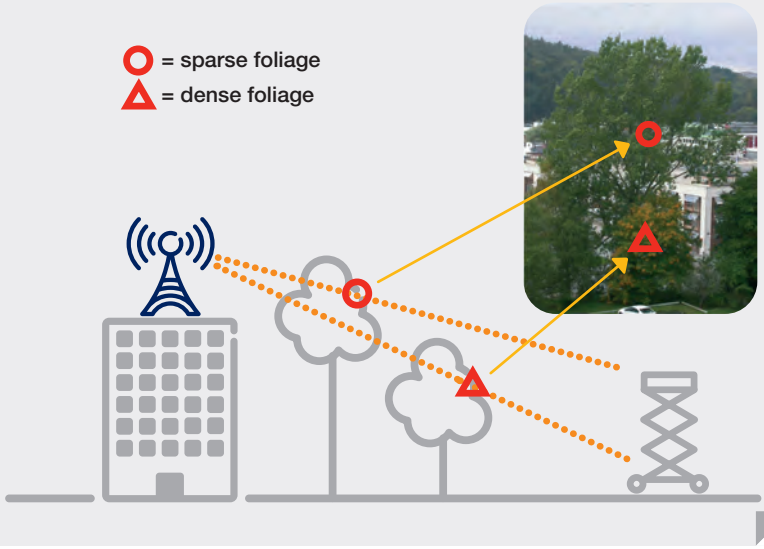
Penetration

As with the case for NLOS reflection, the path loss resulting from penetration is highly dependent on the material of the object blocking the line of sight. The performance of both test systems was measured in a scenario shown in **Figures 5A** and **5B**. The sending and receiving radios were located 150m apart, with one tall sparse tree and a shorter, denser tree blocking the line of sight. The radio placed on the mobile lift was positioned to measure the radio beam first after penetration of the sparse foliage and then lowered to measure the more dense foliage, as shown in Figure 5A. The circle and triangle symbols indicate where the radio beams exit the foliage.

Measurements were carried out under rainy and windy weather conditions, resulting in variations of the NLOS path attenuation, as shown in the received signal spectra for the 28GHz radio link in Figure 5B. Under LOS conditions the amplitude spectrum envelope reached -50dBm. Consequently, the excess path loss for the single-tree (sparse foliage) scenario varied between 0 and 6dB when measured for 5 minutes. In the double-tree (dense foliage) case excess path loss varied from 8dB up to more than 28dB. A complementary experiment showing similar excess path loss was carried out at 5.8GHz.

To summarize, contrary to popular belief, a 28GHz system can be used with excellent performance results using the effect of NLOS penetration through sparse greenery.

FIGURE 5A **Test site for NLOS backhaul – penetration**



Deployment guidelines

So far, this article has covered the key system properties for NLOS propagation – diffraction, reflection and penetration – dispelling the myth that these effects can be used only with sub-6GHz frequencies. The next step is to apply the theory and the test results to an actual deployment scenario for microwave backhaul.

Table 2 shows the indicative throughput for each NLOS scenario, using the measured loss from the examples above together with the graphs in Figure 2.

A trial site, shown in **Figure 6**, was selected to measure the coverage for an NLOS backhaul deployment scenario. Four- to six-story office buildings with a mixture of brick, glass and metal facades dominate the trial area. The hub node was placed 13m above ground on the corner of a parking garage at the south end of the trial area. By using the measured loss in the diffraction, reflection and penetration from the tests as a rule of thumb, an indicative throughput for each NLOS scenario has been taken from Figure 2 and summarized in Table 2.

The colored areas in Figure 6 show the line of sight conditions for the trial site: the green areas show where pure LOS exists; the yellow areas indicate the use of single-path reflection; the blue areas indicate diffraction; and the red areas show where double reflection is needed. Areas without color indicate either that no throughput is expected or that they are outside the region defined for measurement. Measurements were made within the region delineated by the dashed white lines. Referring to Table 2, it is expected that the 5.8GHz system will meet small-cell backhaul requirements (>50Mbps throughput) within a 250m radius of the hub; and the 28GHz system should provide more than 100Mbps full duplex throughput up to 500m from the hub. To test the actual performance, a receiver node

was placed 3m above ground measuring full duplex throughput along the main street canyon and in the neighboring streets. On account of the wide antenna lobe of the 5.8GHz system, realignment was not needed for the hub antenna for measurement purposes. For the 28GHz system, realignment of the narrow antenna beam was needed at each measurement point – a fairly simple procedure even under NLOS conditions.

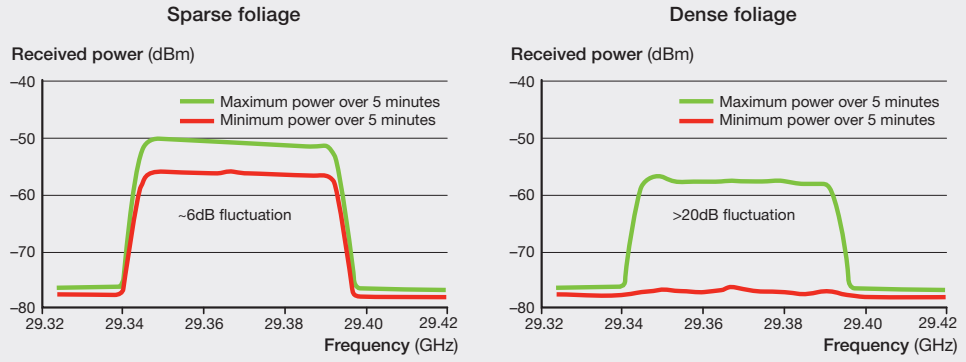
The actual values observed at each measurement point exceeded or matched the predicted performance levels in Table 2. Due to the lack of correctly aligned reflection surfaces, providing backhaul coverage using the double-reflection technique (the red areas of the trial area in Figure 6) was only possible for a limited set of measurements. Multipath propagation, including the reflection effects created by vehicles moving along the street canyon, was significant for the 5.8GHz system, but resulted only in slightly reduced throughput in some of the more difficult scenarios for the 28GHz system.

Summary

In traditional LOS solutions, high system gain is used to support targeted link distance and mitigate fading caused by rain. For short-distance solutions, this gain may be used to compensate for NLOS propagation losses instead. Sub-6GHz frequency bands are proven for traditional NLOS usage, and as shown in this article, using these bands is a viable solution for small-cell backhaul. However, contrary to common belief, but in line with theory, MINI-LINK microwave backhaul in bands above 20GHz will outperform sub-6GHz systems under most NLOS conditions.

The key system parameter enabling the use of high-frequency bands is the much higher antenna gain for the same antenna size. With just a few simple engineering guidelines, it is possible to plan NLOS backhaul deployments that provide high network performance. And so, in the vast amount of dedicated spectrum available above 20GHz, microwave backhaul is not only capable of providing fiber-like multi-gigabit capacity, but also supports high performance backhaul for small cells, even in locations where there is no direct line of sight.

FIGURE 5B **Channel amplitude response – penetration**



Resolution bandwidth: 50kHz

Table 2: Indicative bitrate performance for different NLOS key scenarios

		LOS	SINGLE REFLECTION	DOUBLE REFLECTION	DIFFRACTION*	PENETRATION***
5.8GHz	0-100m	100Mbps	100Mbps	10Mbps**	80Mbps	100Mbps
	100-250m	100Mbps	80Mbps	<10Mbps**	60Mbps	100Mbps
	250-500m	100Mbps	60Mbps	<10Mbps**	10Mbps**	80Mbps
28GHz	0-100m	400Mbps	400Mbps	280Mbps**	400Mbps	400Mbps
	100-250m	400Mbps	400Mbps	185Mbps**	400Mbps	400Mbps
	250-500m	400Mbps	400Mbps	185Mbps**	280Mbps	400Mbps

*30-degree diffraction angle; **not recommended for small-cell backhaul; ***sparse foliage or similar

FIGURE 6 **NLOS backhaul trial area**

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Acknowledgements

The authors gratefully acknowledge the colleagues who have contributed to this article: Jan-Erik Berg, Mikael Coldrey, Anders Derneryd, Ulrika Engström, Sorour Falahati, Fredrik Harrysson, Mikael Höök, Björn Johannisson, Lars Manholm and Git Sellin

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284 23-3190 | Uen
ISSN 0014-0171