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EVALUATION OF COMBINED AVAILABILITY PREDICTION METHODS FOR MULTICARRIER MICROWAVE LINKS

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Nowadays, microwave backhaul can reliably provide several gigabits of capacity, in many cases due to the aggregation of multiple parallel links working at different frequencies. While the availability prediction methods for a single carrier link are well-known and widely applied for link budget calculations, the method for estimating the availability of the multicarrier system's combined throughput (or simply the combined availability) needs to be developed. The purpose of this article is to compare the obtained practical results with software simulation output based on ITU recommendations, as well as to evaluate the theoretical approach to combined availability calculation of a multicarrier link. The results showed a correlation between experimental and theoretical methods, as well as a results deviation between different theoretical models including the ITU-based model, which will be discussed herein.

Keywords: Microwave, multicarrier, propagation, availability estimation, rain fading, multipath fading

1. Introduction

Backhaul requirements for 5G and beyond are driving operators to explore combined microwave (MW) and millimetre-wave (mmWave) solutions, particularly aggregating traditional 6/18 GHz bands with emerging E-band (70/80 GHz) links. However, while high-frequency links offer greater bandwidth, they suffer from severe rain attenuation and atmospheric absorption (Fencl *et al.*, 2020; Samad *et al.*, 2021). In contrast, lower-frequency MW bands exhibit much lower rain fade but limited capacity. A multi-band approach aims to exploit complementary characteristics: The E-band delivers peak rates under clear-sky conditions, while the MW band maintains connectivity during adverse weather.

Despite extensive studies on single-band performance, research on combined availability for dual-band systems remains limited. Crane's rain attenuation model often yields better results than the ITU-R P.530-18 recommendation for high-frequency links (Hilt, 2019; Samad *et al.*, 2021); however, its applicability in a multi-band context has not been fully validated in the context of real field measurements. Recent work by Diba *et al.* (2021) employed supervised learning to quantify rain effects on K-, Ka-, and E-band links, underscoring the need for accurate prediction under heavy precipitation. Moreover, atmospheric factors beyond rain, such as water vapour and cloud attenuation, can contribute a non-negligible loss at 80 GHz (Fencl *et al.*, 2020), suggesting that ITU-R P.840 cloud/fog models should be integrated into availability estimates.

Several experimental campaigns have investigated dual-frequency links. Larsson and Bao (2020) reported on a 7 km parallel 18 GHz and 80 GHz deployment, demonstrating that combined operation can sustain 99.99% availability even in regions with intense rain. Similarly, Trinos and Tan (2022) applied ITU-R methods to predict the joint availability of 71.6/81.6 GHz and 11 GHz links, confirming significant reliability gains. These studies provide valuable benchmarks but often lack comprehensive statistical uncertainty and fog attenuation analyses.

In this paper, we present a six-month field study of a 2.33 km dual-band link in Riga, Latvia, comparing experimental availability data with predictions from ITU-R P.530-18, Crane, and the Vigants–Barnett model. We also incorporate ITU-R P.840 fog attenuation calculations to assess their impact on link performance. Our results reveal that Crane's model best matches observed rain outages for the E-band component, while the MW link effectively smooths combined availability. We quantify confidence intervals for each model and discuss the implications for planning robust 5G backhaul networks.

2. Methodology

The methodology consists of parallel theoretical and experimental approaches to evaluate the combined throughput availability of a dual-band microwave link.

On the theoretical side, we follow a procedure based on established propagation models and standards. First, the correlation of rain fading and multipath fading events between the two frequency bands is characterised. In particular, since both bands share the same path, rain fades are assumed to be fully correlated across the bands (i.e., both links experience rain simultaneously), whereas multipath fades are treated as largely independent due to the widely separated carrier frequencies. This assumption is supported by propagation theory, deep multipath fades on distinct hops or widely spaced frequencies tend to be uncorrelated. Next, given the fade event correlation assumptions, we define the total outage probability for all possible combinations of link states. In essence, we compute the probability that either one or both links are in a faded state at the same time, depending on whether the fading cause is rain or multipath. For independent fading events (e.g. multipath on widely separated frequencies), the combined outage probability can be approximated by the sum of individual outage probabilities (inclusive OR of independent events). For fully correlated events (e.g. rain affecting both links simultaneously), the combined outage is dominated by the worst link (in this case, the higher-frequency link) and is not simply additive.

These principles follow the guidelines in ITU-R P.530-18 for combining outages on multiple hops, which we adapt to multiple carriers on the same path (International Telecommunication Union (ITU-R), 2021). Using these probabilities, we then estimate the combined availability (the complement of outage probability) for the multiband link. This is implemented via software simulation, described below, to handle the many possible link state combinations and their associated probabilities. The theoretical availability analysis considers two alternative models for each propagation effect, reflecting common industry approaches. For rain attenuation, we apply either the ITU-R rain fading method (as detailed in ITU-R P.530-18) or the well-known Crane model (Crane, 1980) as a comparison.

For multipath fading (clear-air, frequency-selective and flat fades), we consider the default method of ITU-R P.530-18 (which is geared toward average terrain and climate) and the Vigants–Barnett model (Barnett, 1972; Vigants, 1975) as an alternative. The Vigants–Barnett model is a classic empirical model that incorporates flat fade margin, frequency, distance and C factor into fade depth predictions (Basile *et al.*, 2010), and it has historically been used for microwave link design alongside the ITU method. ITU model excludes C factor, but additionally incorporates geoclimatic K factor, link inclination, the mean path terrain clearance, the lowest antenna altitude (above sea level) and subrefractive parameter (International Telecommunication Union (ITU-R), 2021). By considering both Crane vs. ITU for rain, and Vigants–Barnett vs. ITU for multipath, we generate four combinations of theoretical predictions. This allows us to examine the sensitivity of combined availability estimates to the choice of model for each fading mechanism.

On the experimental side, we gathered real performance data from a dual-band link over an extended period and calculated the actual combined throughput availability. Specifically, a dedicated dual-band test link (described in detail in Section 4.1) was monitored continuously for a period of 6 months. Key radio performance parameters – including the modulation rate (modulation coding scheme) and error metrics of each link – were recorded at a high temporal resolution (sampling interval of 10 seconds). These raw measurements were processed to derive the instantaneous throughput delivered by each radio in each direction. We then summed the contributions of the two bands to obtain the total aggregated full-duplex throughput available at each time sample. By tracking the total throughput time-series, we could determine what fraction of time the combined link capacity was at or above any given value.

This empirical cumulative distribution of capacity directly yields the availability vs. throughput behaviour of the dual-band system. In other words, the experimental combined availability is computed as the percentage of time the total throughput meets or exceeds a target rate (e.g., 5 Gbps, 10 Gbps, etc.). Finally, we compare the measured availability curve with the theoretical predictions from the simulation. The comparison, presented in Section 4, highlights how well the models agree with reality and under what conditions they diverge. The overall process allows us to validate the theoretical approach for combined availability and to identify which propagation model (ITU or alternative) best matches the empirical results.

By employing both theoretical modelling and experimental validation, our methodology ensures a comprehensive evaluation. The ITU-R recommended approach (for multi-hop links) is extended to a multi-frequency scenario, and its predictions are cross-checked against field data. Prior studies have taken a similar combined approach – for example, Kouchaki and Dabibi (2020) performed simulations and testbed measurements for an 11 GHz + 80 GHz link aggregation, highlighting the benefits of multi-band backhaul for 5G networks.

3. Theoretical approach based on ITU recommendations

For a multicarrier system sharing the same propagation path, it is necessary to evaluate the combined availability of two or more communication channels, given that each of them may have different degrees of performance degradation due to multipath/rain fading.

The method of evaluating the combined availability of multiple links is given in §2.3.7 and §2.4.6 of the recommendation ITU-R P.530-18.

§2.3.7 deals with multipath fading (both frequency selective and flat) in tandem networks in clear-air conditions (no precipitation). The recommendation considers simultaneous fading occurrence on adjacent hops, which means they have different propagation paths and terrain profiles. Thus, deep multipath fades on adjacent hops are almost completely uncorrelated. Therefore, an upper bound to the total outage probability for clear-air effects can be obtained by summing the outage probabilities of the individual hops. A closer upper bound on the link of n hops can be estimated from:

$$P_T = \sum_{i=1}^n P_i - \sum_{i=1}^{n-1} (P_i P_{i+1})^K \quad (1)$$

with

$$K = 0.5 + 0.0052A + 0.0025(d_i + d_{i+1}), \quad (2)$$

where P_i is the outage probability predicted for the i -th of the total n hops and d_i is the path length (km) of the i -th hop (International Telecommunication Union (ITU-R), 2021).

If this logic is to be applied to the same propagation path shared by the dual-band link under test, then the following assumptions can be made:

- 18 GHz and 80 GHz are uncorrelated over the same terrain in terms of multipath fading due to having different wavelengths.
- Multipath has a negligible effect on 80 GHz.
- The partially correlated case equation can be used as the closest approximation.

This means that the occurrences of multipath fading in E-band and MW-band links can be considered as two uncorrelated inclusive sets of events (Lind *et. al.*, 2003) (refer to Fig. 1). According to the general rule of addition, the combined multipath unavailability of the dual-band link can be estimated as:

$$P_T(\text{multipath}) = \sum_{i=1}^n P_i - \sum_{i=1}^{n-1} (P_i P_{i+1}), \quad (3)$$

given that the correlation coefficient $K = 1$, which corresponds to a more conservative approach with $P_T = \max$.

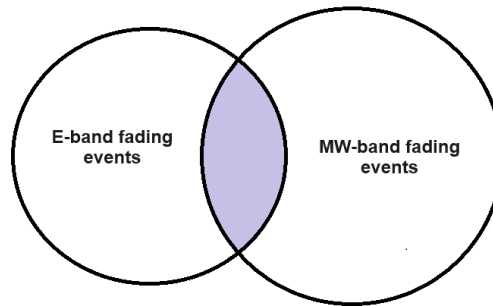


Figure 1. Uncorrelated inclusive sets of events of multipath fading

§2.4.6 deals with rain fading in a tandem network. It is stated that if precipitation events are correlated over a finite area, then the attenuation on two or more links of a multi-hop relay system will also be correlated, in which case, according to the special rule of addition, the combined fading probability may be written as:

$$P_T(\text{rain}) = K \sum_{i=1}^n P_i, \quad (4)$$

where K is a modification factor that includes the overall effect of rainfall correlation.

The multicarrier link over the same path is fully correlated in terms of rain fading, i.e., all aggregated channels will experience the same rain rate at the same time. So K would be equal to $1/n$ if the fading probabilities of all channels were the same (in case of the same frequency and polarisation):

$$P_i = P_{i+1} = \dots = P_n. \quad (5)$$

However, the combination of different bands will certainly have different precipitation effect on each of the channels; thus, it is necessary to define the evaluation criterion. Let us designate the rain fading probabilities of 18 GHz and 80 GHz links as $P_{18\text{ GHz}}$ and $P_{80\text{ GHz}}$ accordingly. These variables reflect the likelihood of two sets of events, which can be termed as independent, fully inclusive events, when one set fully includes the other (refer to Fig. 2). This is based on the following assumptions:

All fading events constituting $P_{18\text{ GHz}}$ outage are included in the set of events constituting $P_{80\text{ GHz}}$ outage. Critical rain rate for 80 GHz is lower than for 18 GHz, and, thus, any fading event that causes 18 GHz outage also does so for 80 GHz.

Not all fading events constitute $P_{80\text{ GHz}}$ outage coincides with the set of events constituting $P_{18\text{ GHz}}$ outage. Consequently, the combined rain unavailability (representing the probability of at least one channel outage) of the dual-band link can be estimated as the probability of the most inclusive set of events.

At the same time, this will correspond to the probability of the critical rain rate, which causes fading of either one channel or both at the same time:

$$P_T(\text{rain}) = P_{\text{critical}} = P_{80\text{ GHz}}. \quad (6)$$

Thus, the rain availability of the low frequency band is irrelevant for calculating the overall availability value, which can be fully defined by the availability of the band more susceptible to precipitation (80 GHz in this case).

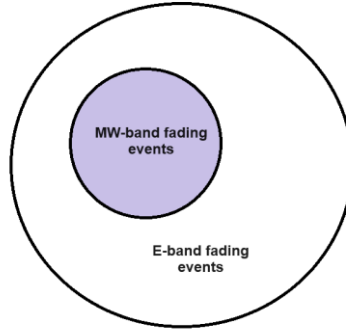


Figure 2. Independent fully inclusive events of rain fading

According to (International Telecommunication Union (ITU-R), 2021), at frequencies where both rain attenuation and multipath fading must be taken into account, the exceedance percentages for a given fade depth corresponding to each of these mechanisms can be added as in the case of exclusive events. This can be confirmed by the empirical observation that multipath fading seldom occurs during periods of heavy rainfall (Bogucki and Wielowieyska, 2006).

Thus, the total fading probability including multipath and rain fading events of a multicarrier system can be obtained by:

$$P_T(\text{total}) = \sum_{i=1}^n P_i - \sum_{i=1}^{n-1} (P_i P_{i+1}) + P_{\text{critical}}, \quad (7)$$

where P_i is the multipath outage probability of each band and P_{critical} is the rain outage probability at the rain rate critical for the multicarrier link.

Given that Adaptive Coding and Modulation/Bandwidth (ACMB) and Band and Carrier Aggregation (BCA) techniques are widely utilized in modern micro/millimetre-wave systems, the probability level of multiple states of a multicarrier system should be considered. That includes all possible combinations of each carrier's modulation/bandwidth states, each combination resulting in certain aggregated throughput of a system. This throughput can be described with a statistical random variable C that can only assume a discrete set of capacity values $\{c_i\}_{i=1}^N$. Each capacity can be associated with a certain outage probability $P_0(c_i)$ ($i = 1, 2, \dots, N$) (Fencl, 2020).

The probability density function of the backhaul link capacity C can be formulated in a continuous domain as:

$$P_r(C) = P_0(c_1) \times \delta(C) + \sum_{i=1}^{N-1} [P_0(c_{i+1}) - P_0(c_i)] \times \delta(C - c_i) + [1 - P_0(c_N)] \times \delta(C - c_N), \quad (8)$$

where $\delta(C)$ is the Dirac delta function (ETSI, 2023). Please refer to the graphical depiction in Figure 3. The outage probability for each capacity value is calculated as the probability of fading occurrence according to (7).

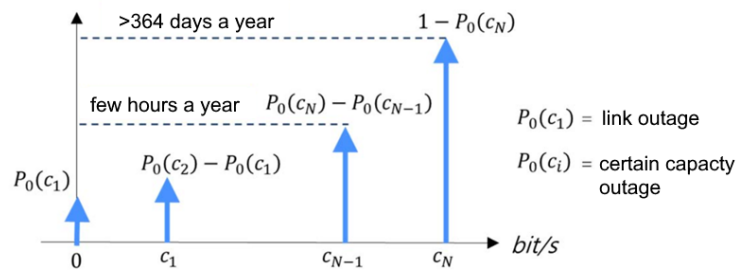


Figure 3. Statistical description of the microwave backhaul link capacity (Fencel, 2020)

4. Experimental setup and data processing

4.1. Test link configuration

The dual-band test link was deployed in Riga, Latvia (urban environment) with a path length of 2.33 km. This link, referred to as the “test polygon,” consists of a pair of collocated point-to-point radios operating at two frequency bands: a traditional microwave (MW) band at 18 GHz and an E-band millimetre-wave at 80 GHz. Both radios are co-mounted on a single dual-band antenna at each end, ensuring they share the same line-of-sight path. The terrain along the path is a developed urban area with significant surface roughness and no large water bodies, which helps minimise specular reflections that could otherwise contribute to multipath fading. A clear line-of-sight was maintained with at least 100% Fresnel zone clearance. The antenna centres were installed at heights of 25 m and 56 m above ground level at the two end sites, respectively, providing a slight downward inclination along the link (approximately 0.9°). The antenna used was a 0.6 m diameter dual-band dish, supporting both 18 GHz and 80 GHz feeds. At 18 GHz, the antenna gain was about 38 dBi, and at 80 GHz it provided about 50 dBi of gain, as is typical for a 0.6 m dish at those frequencies.

The link utilized commercial carrier-grade hardware for both bands. Specifically, an Integra-X radio operating at 18 GHz and an Integra-E radio operating at 80 GHz (both by SAF Tehnika) were installed at each end. The Integra-X units were configured in a dual-polarization mode with XPIC (cross-polarization interference cancellation) to allow two independent data channels (often denoted as channel A and B) on the same 18 GHz frequency, effectively doubling capacity. Integra-E was operating in a single polarization (vertical in this case) at the 80 GHz frequency band. Table 1 summarizes the key radio and modem parameters of the equipment.

Table 1. Dual-band test link radio/modem and antenna parameters

Name	Integra-X Low	Integra-X High	Integra-E High	Integra-E Low
Site name	Point A	Point B	Point A	Point B
Antenna size (m) / gain (dBi)	0.6 / 38.1	0.6 / 38.1	0.6 / 50	0.6 / 50
Antenna height AGL (m)	25	56	56	25
TX frequency (MHz)	18030	19040	84125	74125
TX power at max mod. (dBm)	26	26	15	15
Polarization	V+H	V+H	V	V
Bandwidth (MHz)	112	112	2000	2000
Modulation	4096QAM	4096QAM	128QAM	128QAM
Max. throughput (Mbps)	2208	2208	10000	10000

Both Integra-X and Integra-E support adaptive coding and modulation (ACM), meaning they can step through modulation schemes from high-order (for clear conditions) to lower-order (for faded conditions) to maintain a synchronization between the modems. The 18 GHz radio supports up to 4096QAM modulation in a 112 MHz channel, yielding a maximum throughput of about 2.2 Gbps per channel (thus ~ 4.4 Gbps combined for both XPIC channels). The 80 GHz radio uses up to 128QAM in a 2000 MHz channel, with a maximum throughput of around 10 Gbps. Thus, when both links are at their top modulation states, the dual-band system can deliver a peak aggregated capacity of approximately 12.2 Gbps full-duplex.

Table 2 provides the geographic coordinates of the sites and other path details. Notably, the region’s climate is moderately rainy – the ITU rain climate for Riga corresponds to a rain rate of about 25.7 mm/h exceeded for 0.01% of the time (ITU-R P.837 reference), which we used in our calculations. According to Crane’s global climate map, the area falls under rain region B2 (continental/taiga climate).

Table 2. Dual-band test link geographical parameters

Name	Point A	Point B
Latitude	56 58 42.40 N	56 57 53.24 N
Longitude	024 06 56.77 E	024 08 40.92 E
True Azimuth (°)	130.82	310.85
Path Length (km)	2.33	
Elevation (m)	4.91	9.78
Antenna Height (m)	25	56
Vertical angle (°)	0.88	-0.89
Rain rate not exceeded for 0.01% of time - ITU-R P.837-7 (mm/hr)	25.69	
Rain region – ITU / Crane	E / B2-96 Polar Taiga	

4.2. Link performance data gathering and processing

Performance monitoring on the dual-band link was conducted from July 2022 through December 2022 (a 6-month period covering summer, autumn, and early winter conditions). The radios were configured to report telemetry at 10-second intervals. Each record includes the current modulation state and an error metric (such as mean square error, MSE, which correlates with signal quality) for each channel, as well as the receive signal level (RSL). These parameters allow the determination of the instantaneous throughput. For each 10-second sample, we converted the measured MSE of each radio into the corresponding modulation format in use at that moment (for example, an MSE above a certain threshold might indicate the link is holding 256QAM or higher modulation state, whereas a lower MSE indicates it has shifted to BPSK, etc.).

Using the known modulation-capacity mappings from the equipment specifications, we translated the modulation of each channel into an achievable data rate in Mbps. Because the radios employ adaptive modulation, this essentially yields the capacity of each link as a function of time. We considered both uplink and downlink directions for each channel.

It is important to note that transmitting and receiving modulations can be different at times, thus yielding asymmetrical throughput. Since our interest is in full-duplex (two-way) throughput availability, we summed the uplink and downlink throughput for each channel to get its combined capacity at any time instance. Then, the capacities of all three data channels (18 GHz XPIC channel A, 18 GHz XPIC channel B and 80 GHz channel) were added together to obtain the total instantaneous full-duplex throughput of the dual-band link. In periods of no fading, this total throughput reaches the maximum ~12.2 Gbps, whereas during heavy fading (rain or multipath fade events) the total throughput may drop significantly as one or both links switch to lower modulations and even lose synchronization.

4.3. Fog effect observation

During the monitoring period, we encountered a notable fog event, which is of interest because standard rain models do not account for fog attenuation. In early June 2022, a heavy fog persisted in the area for about 12 consecutive hours (over June 8–9). Both bands experienced additional attenuation during this fog event: the 18 GHz RSL dropped by up to ~3 dB, and the 80 GHz RSL dropped by up to ~7 dB. These attenuations are attributable to absorption and scattering by the tiny water droplets in fog, which can be significant at E-band frequencies (on the order of a few dB/km for thick fog at 80 GHz, according to ITU-R P.840).

The ITU-R P.840-8 recommendation provides a method to predict attenuation from clouds and fog for Earth-space links, based on liquid water density (International Telecommunication Union (ITU-R), 2019). However, this fog modelling is not included in ITU-R P.530 or in our Pathloss simulation tool. Thus, any reduction in throughput caused by fog in our measurements would appear as an additional outage that the theoretical model (which considered only rain and multipath) did not anticipate. We logged the fog event and its impact as part of the experimental data. While fog of that magnitude was a relatively rare occurrence, its effect was clearly observed in the data and is considered in our analysis of discrepancies between measured and predicted availability.

4.4. Software and theoretical models' description

For the theoretical combined availability calculations, we used the Pathloss 6 microwave link planning software. Pathloss 6 features a “carrier aggregation report” capability that can evaluate the combined capacity of parallel links across a range of availabilities. We configured Pathloss with the exact parameters of our 18 GHz and 80 GHz link (antenna gains, frequencies, path geometry, transmit power,

adaptive modulation thresholds, etc.) so that it could simulate performance under the ITU-R models. Pathloss performs a multi-state availability analysis as illustrated in statistical representation in Figure 3: it computes the availability of each possible modulation mode for each link (essentially using known fade margin and attenuation distributions from ITU-R P.530 for clear-air and rain). It then enumerates all combinations of states between the two links and sums the capacities for each combination.

For each combination, it determines the probability of occurrence, taking into account that rain fading of the two bands will be fully correlated (treated as occurring together) whereas multipath fades are treated as independent between the bands (or uncorrelated inclusive events). Pathloss thus produces a predicted distribution of total throughput vs. availability, similar to what we derived empirically in Section 3. We ran the Pathloss simulation multiple times, varying the propagation models as described (using either the default ITU multipath model or a user-defined Vigants–Barnett adjustment, and switching between Crane and ITU for rain).

We noted that Pathloss default algorithm assumes independent multipath fading in each band (which aligns with our assumption of negligible correlation between 18 GHz and 80 GHz multipath fades) and fully correlated rain attenuation, effectively implementing the formulas from ITU-R P.530-18.

Figure 4 illustrates an example output from the carrier aggregation report in Pathloss, showing the combined capacities of both links at various availability levels. These simulation results were exported for comparison with the measured data.

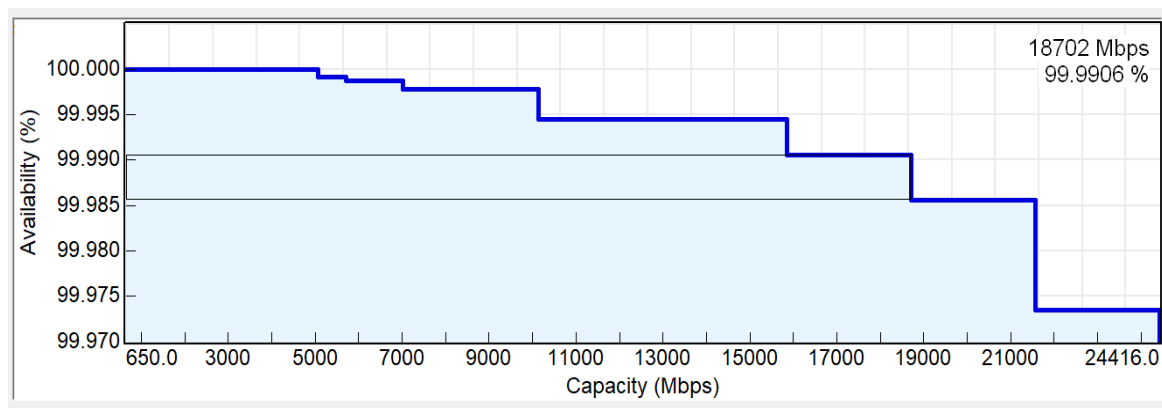


Figure 4. Carrier aggregation report example from Pathloss 6

In summary, the experimental setup provided a controlled dual-band link environment with high-quality equipment and monitoring, and the data processing steps translated raw link metrics into meaningful availability statistics. Simultaneously, the theoretical analysis in Pathloss (incorporating ITU-R and alternate models) yielded predicted availability curves. With both sets of results in hand, we can proceed to compare them and discuss the outcomes.

4.5. Results comparison

Figure 5 presents the throughput–availability curves obtained from the experimental data alongside the theoretical prediction curves from the Pathloss simulations. The curve denoted as “Experimental data” in Figure 5 represents the measured performance of the dual-band link (after processing 6 months of data as described), while the other curves correspond to the different combinations of rain and multipath models used in simulation. For clarity, we denote the theoretical curves as follows: “ITU-R rain, ITU-R multipath”, “ITU-R rain, Vigants–Barnett multipath”, “Crane rain, ITU-R multipath” and “Crane rain, Vigants–Barnett multipath”. In the plotted results, it turns out that the choice of multipath fading model had a negligible impact on the combined availability; the curves using the Vigants–Barnett model versus the standard ITU-R multipath model are virtually indistinguishable. This is because, over a 2.33 km urban path, multipath fading was not a dominant impairment – particularly at 80 GHz, which is mostly immune to multipath due to its very short wavelength. Thus, effectively, two distinct theoretical curves emerge: one for the Crane rain model and one for the ITU-R rain model (each reflecting combined availability of the dual-band link). As expected, the rain attenuation model significantly influences the high-availability end of the curve, since rain fading is the primary factor that limits link uptime at the targeted reliability levels (99.9–99.99% range).

Examining Figure 5, we observe that the Crane-based prediction aligns more closely with the empirical curve than the ITU-based prediction. The Crane model yields a more conservative availability

estimate – i.e., it predicts slightly more outages for a given throughput level, which in this case better matches the real observed outages. For example, at the very highest throughput (around 12 Gbps), the measured availability is quite low because even minor attenuation can knock the 80 GHz link off its highest modulation.

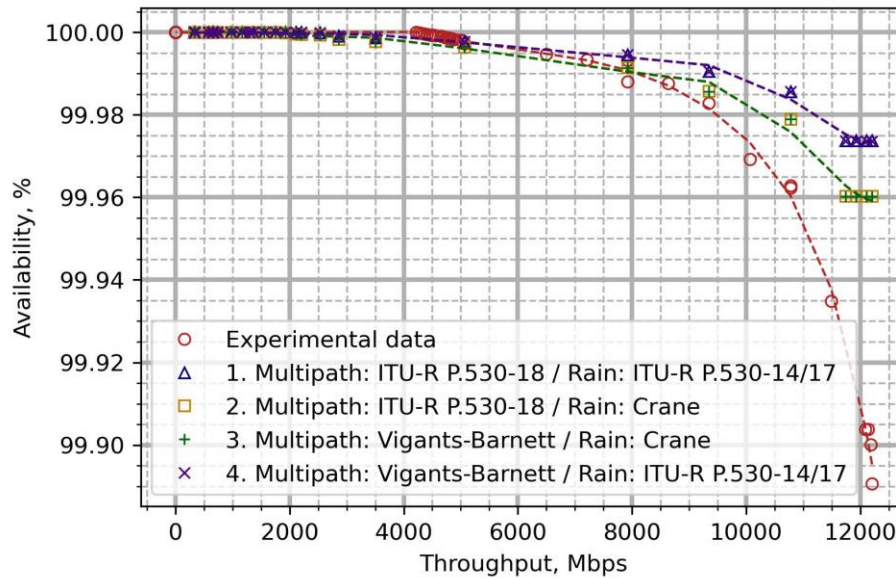


Figure 5. Dual-band link throughput availability obtained using experimental data and different simulation algorithms

The ITU-R model appears to overestimate the availability in this region, predicting that the link should maintain 10–12 Gbps for a larger fraction of time than what was actually measured. The Crane model, in contrast, predicts a sharper drop in availability at the high end, which is closer to the measured behaviour. Quantitatively, for throughput levels above ~10 Gbps, the ITU-R model prediction was overly optimistic – e.g., it predicted roughly 99.99% availability at 10 Gbps, whereas the Crane model predicted ~99.98%, and the measured data showed on the order of 99.97% availability. At the very peak rate (~12 Gbps), the experimental availability was the lowest of all, indicating that real-world factors reduced uptime more than any model anticipated.

In the mid-range throughput (say 5–8 Gbps), all curves – measured and simulated – converge to very high availability (>99.99%). In fact, below about 8 Gbps, the dual-band link was essentially always able to provide at least that throughput during the observation period. This is because even under heavy rain, the 18 GHz link can fall back to a lower modulation and still carry a few Gbps, and moderate rain is needed to start significantly impacting the 18 GHz channel. Meanwhile, light rain or minor fades only affect the 80 GHz link, which might reduce the total from ~12 Gbps to ~10 Gbps, but not below 8 Gbps. Therefore, the differences between models become pronounced only in the tail of the distribution (the highest capacity region).

To facilitate comparison, we fit polynomial trendlines (7th order) through each of the simulation data sets as well as the measured data. These trendlines are shown as dashed curves in Figure 5. They help in evaluating error metrics between the curves. The results confirm that using the Crane rain attenuation model provides a closer match to observed dual-band link performance in our climate. This finding is in line with other studies that have noted differences between rain fade models – for example, Diba *et al.* (2021) reported that certain ITU-based methods can underestimate extreme rain attenuation events in temperate climates, whereas alternate models capture them better.

We also note that both theoretical approaches exceed the measured availability in the upper throughput range, meaning the real link had more downtime than predicted. This gap is relatively significant for the Crane as well as the ITU model. At lower throughputs (where all curves cluster near 100% availability), the agreement is essentially perfect, as even the ITU model correctly predicts that, for example, 5 Gbps would be available >99.995% of the time (and indeed it was, empirically ~100% in our data).

In summary, the combined availability results demonstrate that our dual 18+80 GHz link achieved multi-gigabit throughput with carrier-grade reliability, and the theoretical methods captured the general

behaviour well. The best agreement was obtained when using the Crane rain attenuation model in the availability calculation. The multipath fading model (ITU-R vs. Vigants–Barnett) had negligible effect on the outcome, which implies that for short links or those without strong multipath, simplifying assumptions (like assuming independent multipath outages on each band and summing their probabilities) are adequate. Figure 5 (with experimental vs. simulated curves) provides a visual summary of these findings, and we next discuss the implications and reasons for the remaining discrepancies.

5. Conclusions

In this work, we presented a detailed evaluation of combined throughput availability for a dual-band (18 GHz + 80 GHz) microwave backhaul link, using both theoretical models and an extensive field measurement campaign. We developed a methodology to calculate the combined availability of multicarrier links by integrating rain fading and multipath fading effects, based on the framework of ITU-R P.530-18 and alternative models. On the practical side, we gathered 6 months of performance data from a live dual-band link and derived the empirical availability as a function of throughput. Comparing these two perspectives has led to several key conclusions:

1. **Validation of Combined-Link Modelling:** Treating the multipath fading events of two different frequency bands as independent uncorrelated (i.e., combining their outage probabilities according to the general rule of addition) but the rain fading events – as fully correlated (where one set of events fully includes the other) produced theoretical availability curves whose overall shape and trends agreed closely with measured data. The small mismatches observed fall within expected natural variability and modelling assumptions, demonstrating that standard ITU-R propagation formulas can reliably predict the performance of aggregated multiband links for design purposes, supporting these tools for early-stage design.
2. **Rain Attenuation Model Impact:** Among the models tested, the Crane rain attenuation model aligned more closely with empirical data across nearly the entire availability range, whereas the ITU-R rain model tended to overestimate performance (i.e., underestimate outages), especially at high throughputs. For example, Crane predicted a higher outage probability for >10 Gbps that better matched observations, underscoring rain fading’s dominance in E-band reliability and reflecting similar findings in the literature (Diba *et al.*, 2021).
3. **Multipath Fading and Independence:** Multipath effects proved negligible: whether using Vigants–Barnett or ITU-R multipath models, the availability curves were virtually identical. This confirms that, in clear-air conditions, the two links’ fades are effectively uncorrelated and that rain attenuation overwhelmingly dictates combined availability for short hops.
4. **Theory vs. Measurement Discrepancies:** Measured availability trailed theoretical predictions by a few hundredth of a percent at high throughputs ($\approx > 99.9\%$ availability). This shortfall is largely attributable to unmodeled phenomena—most notably fog and cloud attenuation per ITU-R P.840-8—which were observed during heavy fog events in our measurement period, as well as to the limited six-month data span capturing atypical weather extremes. Minor operational factors, such as uncounted equipment downtime and ACM switching thresholds’ variability, also contributed. Nevertheless, the gap remains modest, underscoring that theoretical models represent median expectations while real-world performance can vary slightly over finite samples.
5. **Practical Design Implications:** Our results demonstrate that a dual 18 GHz + 80 GHz link can sustain ~10 Gbps at $\approx 99.97\%$ availability and multiple Gbps at $> 99.99\%$ in moderate climates—performance unattainable by either band alone. We recommend that network planners adopt conservative rain models (Crane or an ITU-R approach with added margin) and incorporate fog attenuation terms, especially in humid or coastal regions, to avoid under-designing microwave and millimeter-wave paths. These insights support evolving standards (e.g., ETSI mWT recommendations) by confirming that simple outage-addition for uncorrelated events, coupled with careful correlation handling where necessary, yields accurate multiband availability estimates.

In conclusion, this work has provided a thorough analysis of combined availability for a dual-band microwave link, supported by both theoretical modelling and empirical evidence. We found that the theoretical models, particularly with the Crane rain attenuation model, can closely reproduce the real-world performance of a multiband link. The dual-band system achieved the target of multi-gigabit throughput with very high availability, validating the multi-band architecture as a viable solution for high-capacity backhaul. Differences between theory and experiment were explained by identifiable physical factors (fog, statistical variation), indicating that model accuracy can be further improved by addressing those factors.

The study contributes to the understanding of rain attenuation models, multipath correlations, and availability calculation techniques in the context of multicarrier links. It also provides practical insight for engineers deploying E-band + microwave links: specifically, to use robust rain models and account for all weather effects to ensure the combined link meets its expected availability. Future work could extend this analysis to longer-term data and other frequency combinations (e.g., 5 GHz + 80 GHz links over longer paths) to generalize the results.

Additionally, incorporating machine-learning-based prediction refinement (as explored by Diba *et al.*, (2021) and others) might further enhance the accuracy of availability estimates. Overall, the positive correlation between our theoretical and experimental results reinforces confidence in multiband link design methodologies and paves the way for reliable, high-capacity wireless backhaul networks in the 5G era and beyond.

Declaration of Generative AI and AI-assisted technologies in the writing process:

During the preparation of this manuscript the authors did not use Generative AI and AI-assisted technologies and take full responsibility for this declaration.

References

1. Barnett, W. T. (1972) Multipath propagation at 4, 6, and 11 GHz. *The bell system Technical Journal*, 51(2), 321–361. DOI:10.1002/j.1538-7305.1972.tb01923.x.
2. Basile, L. A., Robert, M., Germain, B. (2010) Comparison of microwave links prediction methods: Barnett-Vigants vs. ITU models. In: *Proceedings of Electromagnetics Research Symposium Proceedings*, Xi'an, March, 2010. Available at: https://www.researchgate.net/publication/265799463_Comparison_of_Microwave_Links_Prediction_Methods_Barnett-Vigants_vs_ITU_Models.
3. Crane, R. K. (1980) Prediction of attenuation by rain. *IEEE Transactions on Communications*, 28(9), 1717–1733. DOI:10.1109/TCOM.1980.1094844.
4. Diba, F. D., Samad, M. A., Choi, D.-Y. (2021) The effects of rain on terrestrial links at K, Ka and E-bands in South Korea: Based on supervised learning. *IEEE Access*, 9, 9345–9355. DOI:10.1109/ACCESS.2021.3049825.
5. ETSI. (2023) ETSI Industry Specification Group (ISG) millimetre Wave Transmission (mWT) 028 V1.1.1, 04/2023. New KPI's for planning microwave and millimetre wave backhaul network. Available at: https://www.etsi.org/deliver/etsi_gr/mWT/001_099/028/01.01.01_60/gr_mWT028v010101p.pdf.
6. Fencel, M., Dohnal, M., Valtr, P., Grabner, M., Bares, V. (2020) Atmospheric observations with E-band microwave links – Challenges and opportunities. *Atmospheric Measurement Techniques*, 13(12), 6559–6578. DOI:10.5194/amt-13-6559-2020.
7. Hilt, A. (2019) Availability and fade margin calculations for 5G microwave and millimeter-wave anyhaul links. *Applied Sciences*, 9(23), 5240. DOI: 10.3390/app9235240.
8. International Telecommunication Union (ITU-R). (2019) *Attenuation due to clouds and fog* (Recommendation ITU-R P.840-8). Geneva: ITU. Available at: <https://itu-rpy.readthedocs.io/en/latest/apidoc/itu840.html>.
9. International Telecommunication Union (ITU-R). (2021) *Propagation data and prediction methods required for the design of terrestrial line-of-sight systems* (Recommendation ITU-R P.530-18). Geneva: ITU. Available at: <https://www.itu.int/rec/R-REC-P.530/en>.
10. Kouchaki, M. R., Dabibi, M. (2020) Experiment on high capacity backhaul transmission link aggregation solution for 5G networks. In: *Proceedings of the 26th Conference of Open Innovations Association (FRUCT)*, Yaroslavl, April 2020. IEEE, 1-6. DOI:10.23919/FRUCT48808.2020.9087444.
11. Larsson, C., Bao, L. (2020) Availability of 7 km-long parallel 18 GHz band and E-band links for multi-band solutions. In: *Proceedings of the 14th European Conference on Antennas and Propagation (EuCAP)*, Copenhagen, March 2020. IEEE. DOI:10.23919/EuCAP48036.2020.9135791.
12. Samad, M. A., Diba, F. D., Choi, D.-Y. (2021) A survey of rain attenuation prediction models for terrestrial links—Current research challenges and state-of-the-art. *Sensors*, 21(4), 1207. DOI:10.3390/s21041207.

13. Trinos, J. P., Tan, G. P. (2022) Combined rain availability of 71.6/81.6 GHz and 11 GHz multi-band solution. In: *Proceedings of the 2022 IEEE International RF and Microwave Conference (RFM)*, Kuala Lumpur, December 2022. IEEE, 1-4. DOI:10.1109/RFM56185.2022.10065286.
14. Vigants, A. (1975) Space-diversity engineering. *The Bell System Technical Journal*, 54(1), 103–142. DOI:10.1002/j.1538-7305.1975.tb02828.x.