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Maturity and field proven experience of millimetre wave transmission

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Executive Summary

Equipment for fixed service point-to-point communication using millimetre waves has been used in trials and commercial telecom grade installations for more than ten years. A wealth of data and experience have been gained during this period and the technology has matured to be stable, reliable and well understood, ready for supporting current and next generation high capacity mobile networks. The present document is a white paper prepared by the ETSI Industry Specification Group (ISG) on millimetre Wave Transmission (mWT) [1] summarizing the experiences gained in some of these trials and installations.

The document covers experience and measurement results from fourteen independent trials; seven E-band (71-76 GHz and 81-86 GHz), six V-band (57-66 GHz), and one mast sway trial. The E-band is typically used for traditional point-to-point high capacity applications while the V-band is characterized by high oxygen absorption and an unlicensed spectrum making it susceptible to interference from other V-band installations. The trials have various ambitions and scopes ranging from long-term, km range E-band deployments to short term installations using e.g. V-band in short reach, street-level deployments for small cell backhaul applications.

It is shown that E-band technology in traditional Line-of-Sight (LOS) installations is a mature technology providing carrier-grade performance with Gigabit-per-second (Gbps) capacities over links several kilometres long. The V-band trials show excellent performance when deployed properly. Furthermore, it is shown that link planning with a deterministic availability can be done using propagation and prediction models provided by ITU-R.

Introduction

To meet current and future traffic demands in mobile networks and the associated increased challenges for the next generation transmission networks for backhauling and fronthauling, ETSI ISG mWT [1] aims to facilitate the use of:

- the V-band (57 - 66 GHz);
- the E-band (71 - 76 & 81 - 86 GHz);
- and, in the future, higher frequency bands from 50 GHz up to 300 GHz (or in wavelengths from 6mm down to 1mm).

ETSI ISG mWT envisions that established and emerging broadband transmission services would benefit from the high-speed wireless transmission that millimetre wave spectrum technology can accomplish. The ISG intends to be a worldwide initiative with global reach that will address the whole industry value chain with particular emphasis on sharing information. This will favour faster and more effective decisions and the investments needed to provide new technologies, features and equipment. This involves sharing information and providing input on current and future regulations and licensing schemes for the use of suitable spectrum in different countries. The ISG also aims to influence standards for the deployment of products and enhance the confidence of all stakeholders and the general public in the use of high-speed millimetre wave technologies.

Scope

The main scope of this document is to provide information about the collected field-proven experience from different millimetre wave trials. The trials have been made independently by different members of the ETSI ISG mWT. The document provides information on the following topics:

- Millimetre wave technology overview
- Overview and status of propagation and availability models
- Field-proven experience from different millimetre wave trials

Characteristics of millimetre wave transmission

Spectrum

The current interest in millimetre wave bands is due to the large amount of bandwidth that lies in this part of the electromagnetic spectrum. Taking into account current regulatory regimes, V-band typically offers 7 GHz bandwidth of contiguous spectrum (57 - 64 GHz), extendable to 9 GHz whenever the 64-66 GHz is open for fixed services. E-band provides twice 5 GHz bandwidth, namely 10 GHz aggregate spectrum (71 - 76 GHz and 81 - 86 GHz). Similarly, at frequency bands above 100 GHz, there are blocks of plentiful spectrum which could be allowed for extra bandwidth for future broadband wireless transmission services.

Parts of the V-band are characterized by high oxygen absorption that implies shorter communication links but at the same time also causes less interference to neighbouring links, especially when combined with narrow beam antennas, which can enable a higher frequency re-use. The license regime is mostly unlicensed or light licensed (country dependent). V-band links might however be susceptible to unpredicted interference when used in very dense deployments in unlicensed bands.

Since 2000, regulators have made available high frequency bands at 71-76 GHz and 81-86 GHz. This so-called E-band enables Gbps data rates given the huge amount of available spectrum (10 GHz) without any oxygen absorption, thus allowing longer links compared to V-band.

A recent overview of the status of worldwide regulation of E-band and V-band is provided in an ETSI ISG mWT white paper [2].

Given the different nature of the two bands, different deployment scenarios might be foreseen for each of them, including macro and small cell backhaul, front-haul applications, Line-of-Sight (LOS) today and maybe near Line-of-Sight (nLOS) or Non-Line-of-Sight (NLOS) in the future. The ETSI Group Specification GS mWT 002 [3] gives an overview of different use cases for millimetre wave transmission and it also addresses deployments.

Traditional line-of-sight

The traditional deployment scenario for macro backhaul is Line-of-Sight (LOS) where E-band technologies can provide high-capacity backhaul with high availability on links up to several km long. Figure 1 depicts the path attenuation as a function of frequency for different rain intensities and has been calculated using references [5] and [6]. The oxygen absorption peak around 60 GHz is very noticeable but it can also be seen from the figure that there are only marginal differences in rain attenuation at frequencies above 60 GHz. Figure 2, which also takes the rain cell size into account [9], illustrates the potential at 140 GHz band for realistic link gains. For example, by using 42 dBi antennas (about 10 cm antenna size), 10 dBm Tx power, and assuming a -60 dBm Rx threshold, a link gain of 154 dB can be achieved which gives a maximum hop length of 1 km at 50 mm/hr rain intensity.

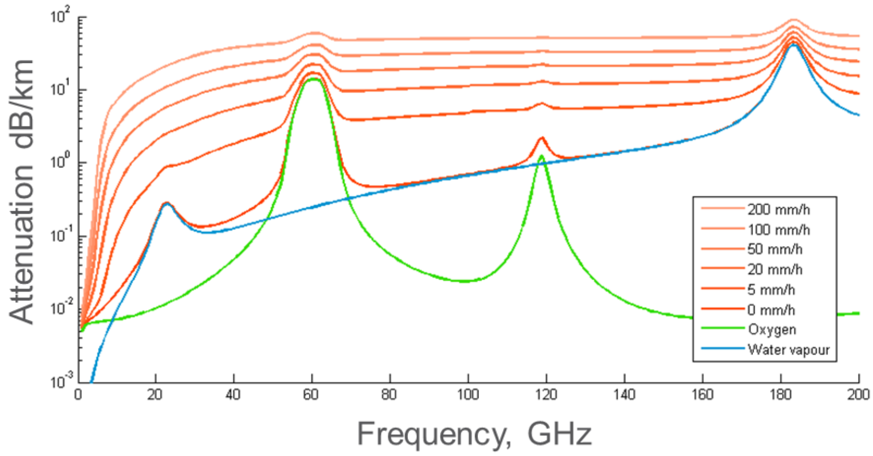


Figure 1: Path attenuation in LOS at different rain intensities.

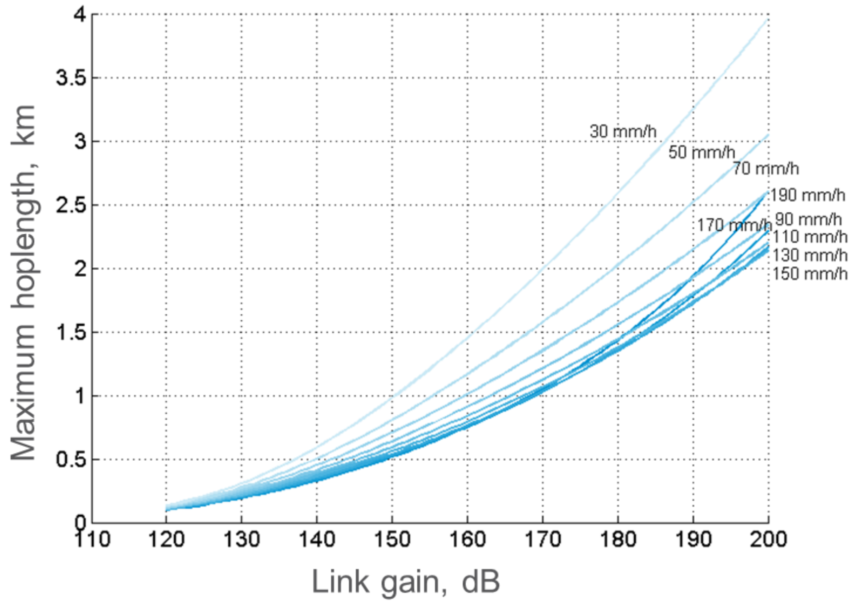


Figure 2: Maximum hop length with 143 GHz carrier for different rain intensities.

Non-traditional near- or non-line-of-sight

Future small-cell deployments and to some extent also macro deployments in e.g. urban scenarios will benefit from a wireless backhaul that can operate in nLOS or NLOS conditions. There is limited information available on millimetre wave field trials in these conditions and the topic is still more on a research level. The propagation loss, due to e.g. diffraction, is substantial at millimetre wave frequencies which on the one hand limits the hop length. But on the other hand, the hop lengths are expected to be quite short in dense urban deployments.

Deployment issues

Traditional planning is needed for traditional LOS deployment of any kind of microwave or millimetre wave radio link. The planning involves calculations of path attenuation, fade margin with associated availability requirements, interference, frequency planning and antennas, etc. The major differentiator between lower microwave frequencies and millimetre wave frequencies is that the use of millimetre wave frequencies are associated with higher path attenuation, especially in bad weather conditions like heavy rain, which limits the hop length. But given a certain antenna area, higher frequencies will result in larger antenna gain which increases the system gain. A high gain antenna also implies a narrow beamwidth which reduces interference but also needs more careful antenna alignment. A typical antenna half power beamwidth (HPBW) is just below one degree for a one foot (30 cm) E-band antenna which puts some requirements on alignment and mast movements. In typical mast structures this is not a problem but it may cause problems if installed on weak structures such as billboards. Mast sway trials are also reported in this white paper.

Non-traditional deployments like street-level deployments of small cell backhaul need more careful consideration and planning. Planning becomes more difficult due to reflections etc. that may cause unpredictable interference to neighbouring links. It may also be difficult to align the antennas in a good way if the nodes are in NLOS from each other. Another issue with street level deployments is movement of vehicles along streets that may introduce time varying reflections in the channel or even block the LOS path. On street level there will likely be less rigid mounting structures available and for example lamp posts and other weaker structures will likely have to be used which may cause problems with antenna movements in heavy wind. However, on street level the hops will be short and smaller antennas with wider beamwidths can be used, making alignment easier even in windy conditions. A small form factor is also required for aesthetic reasons in street deployments. For example, an 11 cm large V-band antenna has about three degree HPBW which makes it easier to handle movements in less rigid mounting structures – a finding that is also supported by the mast sway trials.

Overview and status of propagation and availability models

The ITU-R Recommendations mentioned below are applicable to the whole range of frequencies envisaged for terrestrial LOS Radio Systems. Nonetheless, the main scope of the trials described in the whitepaper is to validate the models for mm-wave and measure performance following the Recommendations.

Propagation

The design of terrestrial LOS radio systems is based on the calculation methods described in ITU-R Recommendation P.530, the latest version of which is P.530-16 [10].

This Recommendation provides prediction methods for the propagation effects that should be taken into account in the design of digital fixed LOS links, both in clear weather and rainfall conditions, continuously evolving following the development of new theoretical studies and availability of a more extensive database of measurement results. It also provides link design guidance in clear step-by-step procedures including the use of mitigation techniques to minimize propagation impairments. The final outage predicted is the base for other Recommendations addressing error performance and availability.

Currently the most important revisions under study refer to non-clear weather conditions, with potential impact mainly on the design of millimetre band solutions (i.e. V-band and E-band systems).

The first revision presently under discussion refers to a new approach for the calculation of rain effects. It has been decided to improve the present method (based on the calculation of the behaviour at one percentage of time - 0.01% - with extrapolation to the other percentages), by efficiently using the available database which permits the direct calculation for any percentage of time.

The method has been tested against available field results and the final refinements are under discussion.

There is another open point, of vital interest for high-latitude countries, dealing with the effect of wet snow. Studies are running and a revision is expected in the near future.

As far as the NLOS or nLOS applications are concerned, the situation is more complex. No existing recommendations are immediately applicable to Point-to-Point (PtP) systems, even if the general concepts are defined and explained in ITU-R P.1411 [12]. Studies are running to check the extensibility of the current methods to millimetre wave frequency bands, but a solution is not expected in the short term.

Availability

An important open discussion is related to the parameters and definitions of the Availability Objectives, the basis of the design of any radio network. The reference Recommendation is ITU-R Recommendation F.1703 [13] which contains the definition of parameters and numerical objectives.

Availability has been considered for a long time as an indicator of a serious event of inability to provide the required service. A minimum criterion of 10 consecutive seconds of service interruption has been adopted to declare this condition.

Since the advent of packet based networks, it is questioned whether this criterion should still be representative of periods of unacceptable performance.

Alternative criteria have been proposed and currently a Question on the matter is active in ITU.

E-band field experience

This chapter reports measurements and experience from different independent E-band trials. The trials have been conducted by members of the ETSI ISG mWT and the contributors, including their contact details, are listed in the list of authors.

Summary of E-band field experience

Experience from independent E-band field trials is reported by members of the ISG mWT. The results show that predictions using ITU-R models for atmospheric attenuation and rain intensity are in good agreement with empirical measurements and can successfully be used for planning of E-band links. The trials show that the E-band radios provide carrier grade requirements with Gigabit performances in traditional LOS deployments over links several kilometres long.

Long-term measurements

This trial is reported by Ericsson and parts of the content have previously been published in [4].

Scope

The scope of this trial was to collect measurement data over several years and compare the empirical data to predictions attained from ITU-R models. Results from a long-term measurement campaign are presented where path attenuation is measured in different weather conditions for two 70/80 GHz microwave links with Gbps capacity.

Setup

Long-term measurement was conducted between 2009 and 2014. The same prototype E-band radio equipment was first measured in a link of 1km (Link 1) between 2009 and 2010, and then in a link of 1.35km (Link 2) between 2011 and 2014. Site A is common for both links, while Site B was moved once. Figure 3 shows the geographic locations (from Google Earth) of the test links, and the elevation profile of Link 2. Link 1 has a similar profile. The system parameters are listed in Table 1. Received power was measured at the common Site A with a rate of 1 sample per minute. The sampling rate was increased to 1 sample per 10 second from March 2013. Environmental parameters such as rain intensity, rain droplet size, snow intensity, visibility, ambient light were also measured.

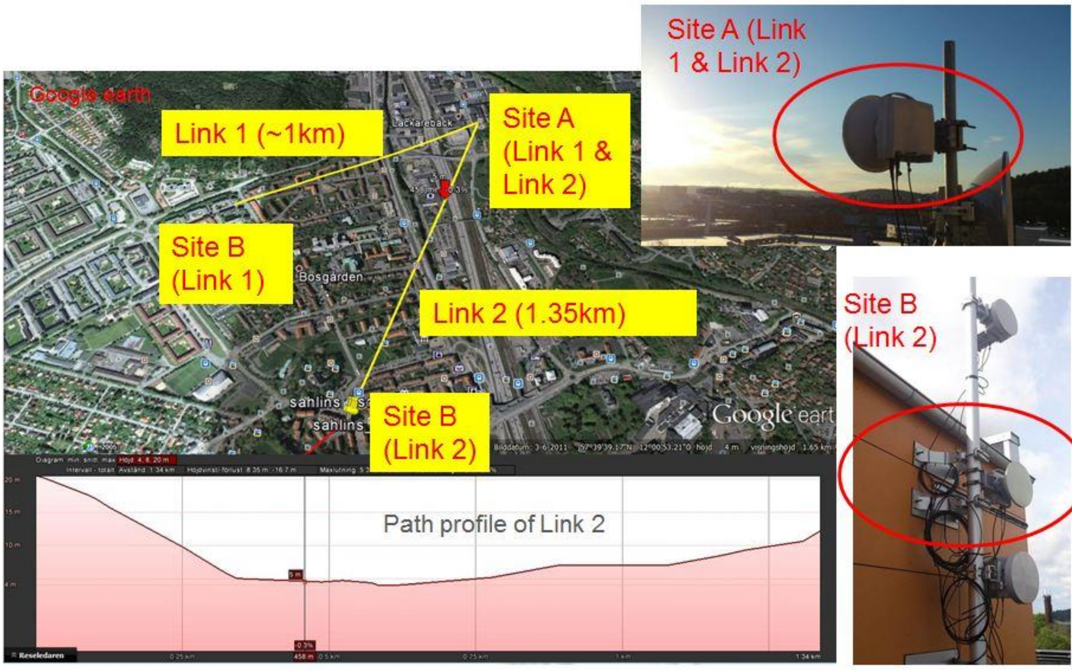


Figure 3: Geographic locations of the two test links.

System parameter	Link 1	Link 2
Carrier frequency	73.5 GHz & 83.5 GHz	73.5 GHz & 83.5 GHz
Transmitter output power	19 dBm	19 dBm
Minimum detectable receiver power	-58 dBm	-58 dBm
Maximum detectable fade	33 dB	30 dB
Antenna gain	43 dBi	43 dBi
Antenna size	0.3 m	0.3 m
Hop length	1.0 km	1.35 km

Table 1: System parameters

Results

Rain distribution

Weather conditions were monitored at the common Site A, using an optical system which is capable of measuring rain intensity, rain droplet size, snow intensity, visibility, ambient light. All parameters were logged with a period of 1 minute. In Figure 4, the measured statistics of rain intensity are compared with the ITU-R Recommendation P.837-5 [11]. The rain intensity distribution over the entire five years is in good agreement with the ITU-R Recommendation. The same figure also depicts the variation of the rain intensity distribution over each individual year from 2009 to 2014, which shows less agreement with the ITU-R model since the model is based on more long-term statistics.

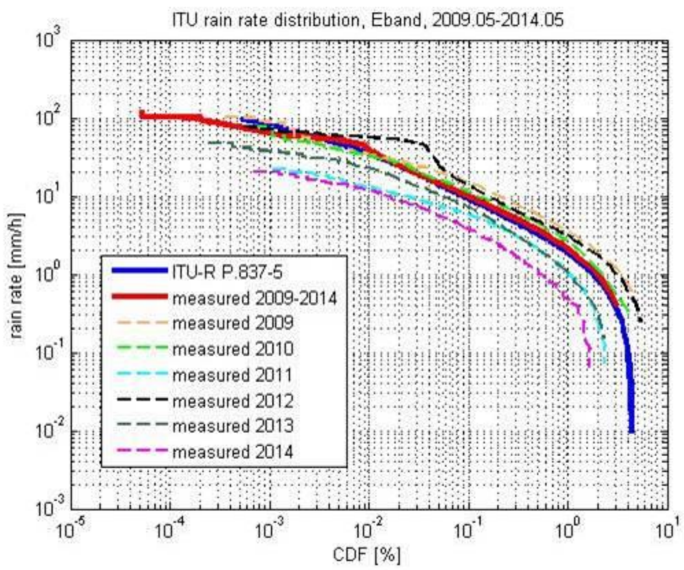


Figure 4: Rain intensity statistics for 2009-2014.

Fade distribution

As expected, power attenuation for short links is mainly due to hydrometeors. Figure 5 shows measured rain intensity and received power at the common Site A, which are highly correlated. Power attenuation associated to fog was measured to be at any time no more than 5dB from the both links.

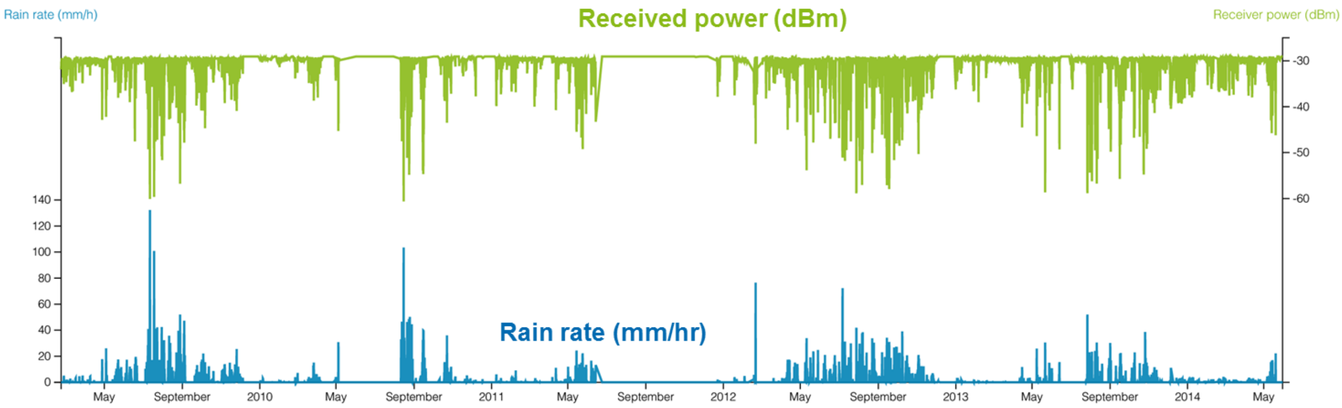


Figure 5: Received power versus rain intensity.

Figure 6 shows the measured statistics of path attenuation versus expected rain attenuation calculated from the ITU-R Recommendation P.530-15 [9]. Attenuation calculated based on measured rain statistics is also included. In general, the measurements are in good agreement with the ITU-R Recommendation. Low attenuations have higher measured probability than predicted by the ITU-R model, which is probably due to other atmospheric impact than rain. In the high attenuation region, the measured probability is slightly lower than predicted by the ITU-R model, which could be explained by the shortage of heavy rain.

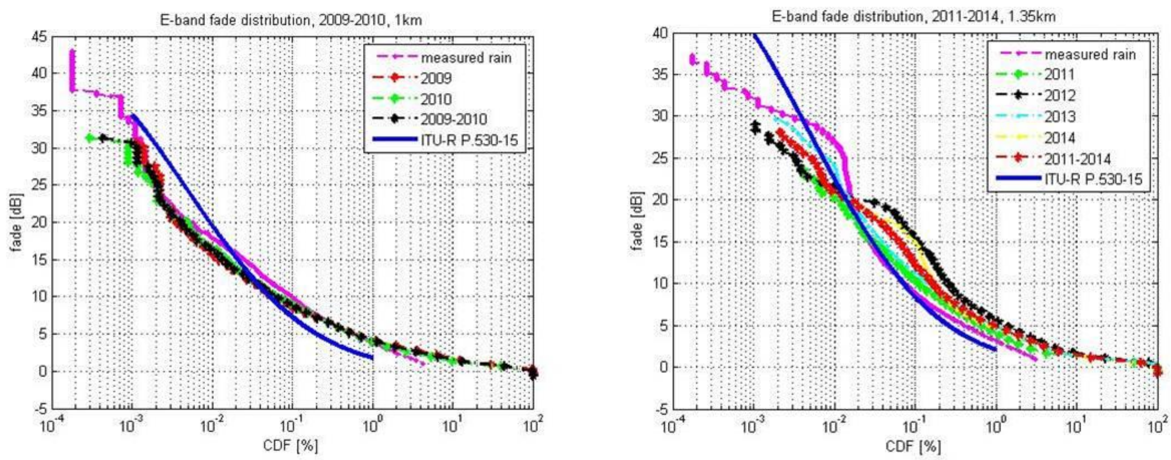


Figure 6: Fade statistics: a) 2009-2010 for Link 1, b) 2011-2014 for Link 2.

Conclusions

We have measured the path attenuation caused by hydrometeor events for an installed 70/80 GHz microwave prototype link over both 1 km and 1.35km. Measured rain intensity and path attenuation statistics vary from year to year, while long-term empirical results are with very good agreement compared to predictions using ITU-R Recommendations. Attenuation caused by hydrometeors other than rain is at any time less than 5dB.

Performance comparison between 38 GHz and 80 GHz radios

This trial is reported by Vodafone.

Scope

Trials were completed in Budapest in order to investigate the behaviour of E-band radio in rainy weather conditions and to compare its performance to a 38 GHz radio.

Setup

The E-Band 80 GHz link was deployed in parallel with the 38 GHz link over a 1800m hop in clear LOS. The trial focused on the comparison of measured Received Signal Levels (RSL) of the two links during a three week period. An Ethernet tester was used to monitor the instantaneous throughput variations of the links. The tester and the radios were accessible remotely through the Vodafone IP network. Figures Figure 7 and Figure 8 show the path profile and parameter configurations, respectively.

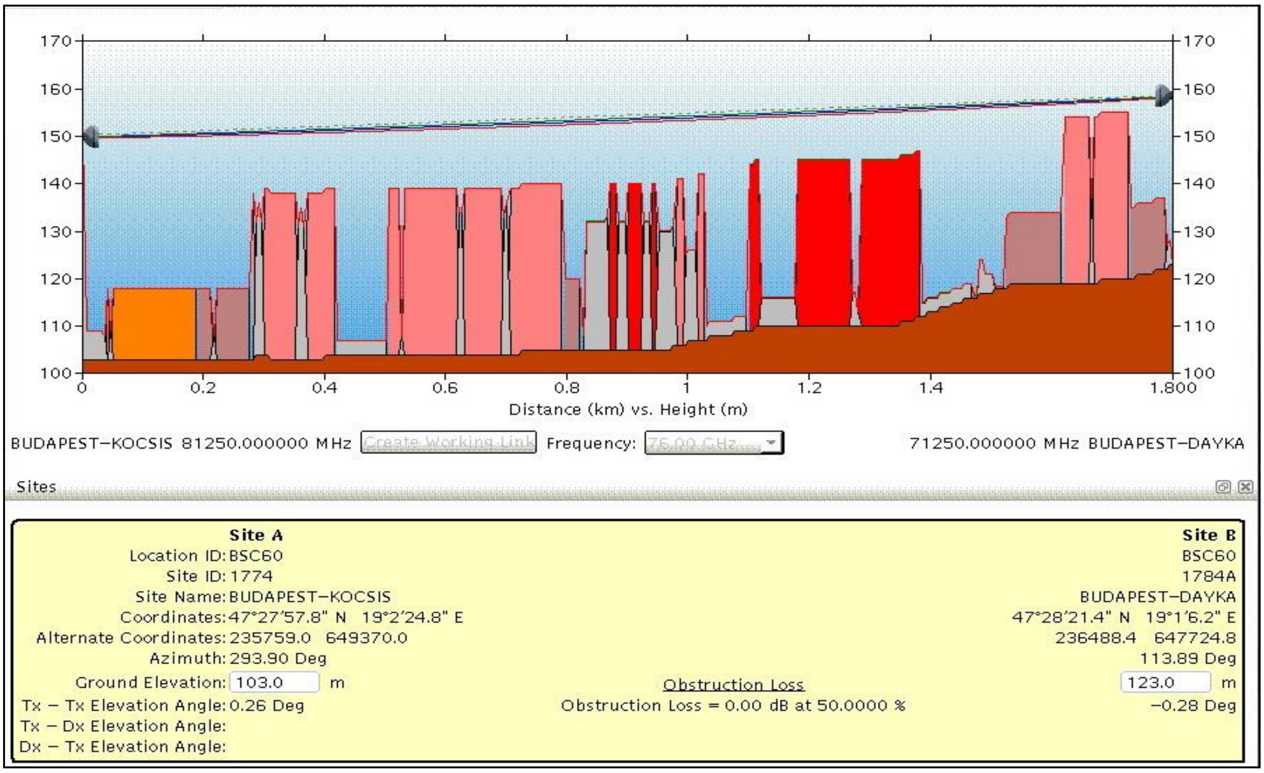
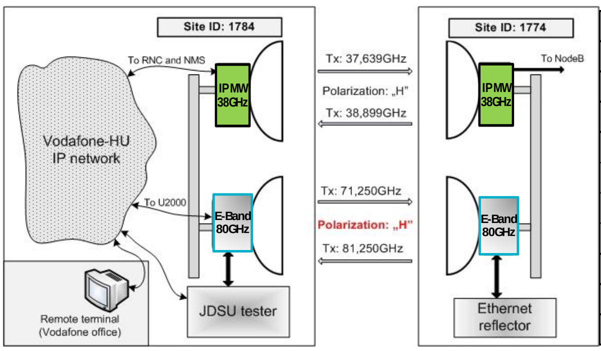


Figure 7: Path profile and coordinates



Parameter	E-Band MW	E-Band MW
Link ID	TM56031S-AIR	VM56031S-5S
Band (GHz)	80	38
Duplex spacing (GHz)	10	1,26
Max Tx power (dBm)	12	14
Calculater Rx level (dBm)	-36,5	-36
ATCP	Disabled	Disabled
Polarization	Horizontal	Horizontal
Antenna diameter (m)	0,3	0,3
Configuration	1+0	1+0
ADM auto power adjust	On	On

Figure 8: Trial configuration and RF parameter setting

Results

The measured RSL values were collected from the Network Management Systems (NMS) of the radios. Both NMS tools provide Min- Max- and Average RSL values measured in every consecutive 15 minute period. It is presumable that the measurement inaccuracy of the two NMS systems is not higher than ±1 dB.

Figure 9 shows the impact of nine rain attenuation events that were captured and which influenced the investigated 38 and 80 GHz links. For reference the “Clear sky” case is also shown.

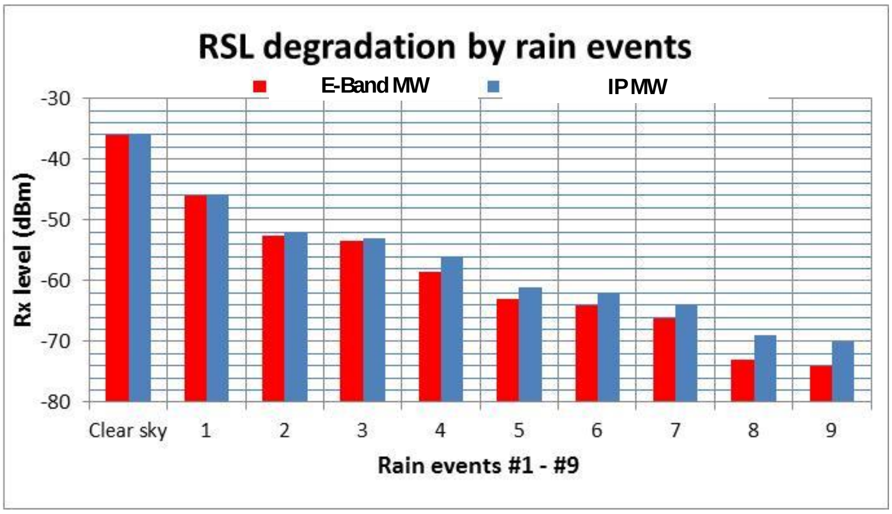


Figure 9: Comparison of rain attenuation (38GHz “H”, 80GHz “V”)

Rain-rate estimation

Based on ITU-R Recommendation P.838-3 [6], the rain rate could be estimated from the measured Rx attenuation values and the corresponding results are shown in Figure 10.

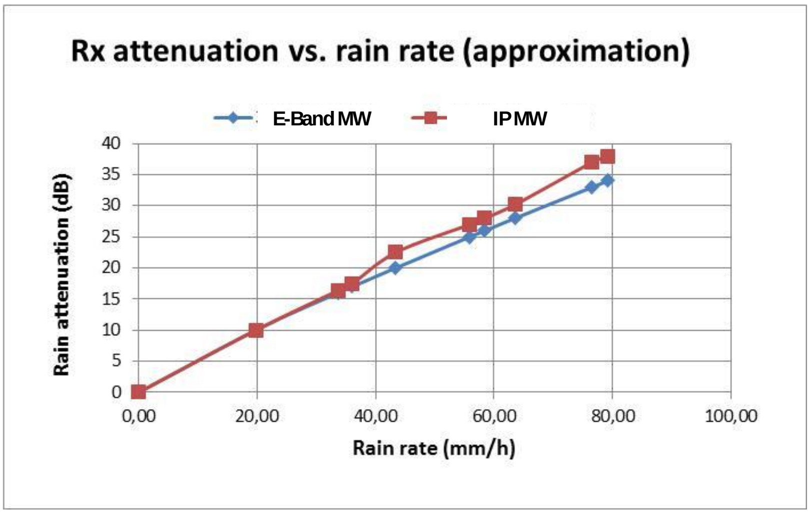


Figure 10: Rain rate vs. rain attenuation (approximation)

However, it should also be noted that the graphs are valid only in the case when the rain cell overlaps the whole link path, i.e., when the rain density is constant between the two sites.

Conclusions

Measurements show that the E-band radios can be used to fulfil high capacity short-hop requirements. They are almost "as good as" the radios in the 38GHz band. An extra 2-4 dB maximum atmospheric attenuation should be taken into account to reach the same link quality.

This is not a serious disadvantage because in most cases (short hops) enough fade margin can be provided by proper link planning to meet the required availability targets.

The increment in atmospheric attenuation experienced is consistent with ITU-R Recommendation P.676-7 [5]. IQ-Link, a microwave (MW) link planning tool used by Vodafone Hungary, uses this Recommendation for prediction calculations. Consequently, during MW link planning activity it is not necessary to pay attention to that extra attenuation as the planning tool automatically takes care of it.

Availability predictions in Basingstoke, UK

This trial is reported by Vodafone and Huawei.

Scope

The aim of the trial was to investigate the performance of E-Band technology by analysing the field performance of a commercial E-band radio. The main objectives of the trial were:

- Measure link availability versus rain rate
- Measure adaptive performance versus rain rate
- Measure link throughput versus rain rate
- Validate ITU-R propagation model P.530-14 [8] and P.530-13 [7]

Finally, a validation of the attenuation due to fog (ITU-R P.840-5 [14]) is done by analysing some fog events during the trial.

Setup

The E-Band trial was held in Basingstoke, UK. Three sites were connected in LOS (Line Of Sight) with a common hub where the measuring instruments were installed.

The lengths of the hops between hub and selected sites are summarized in Table 2.

Site Type	Distance from Hub [km]
Hub	-
Site #1	2.15
Site #2	2.6
Site #3	3.4

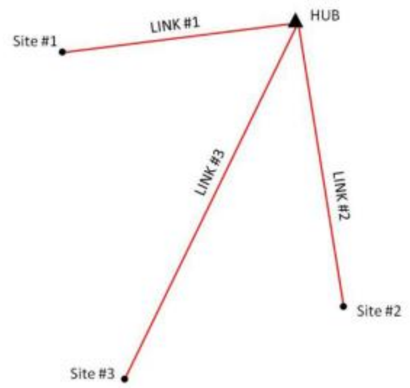


Table 2: Hop lengths in E-Band trial

Considering that all hops were foreseen to be configured with Adaptive Modulation (AM), link budgets were done by assuming QPSK Strong as reference mode. 64QAM was assumed as nominal mode. All links budgets have been done assuming 0.3 m antenna with 43.5 dBi gain. The assumed rain intensity R0.01% (exceeded for 0.01% of the time) was 35 mm/h. The trial configuration is illustrated in Figure 11.

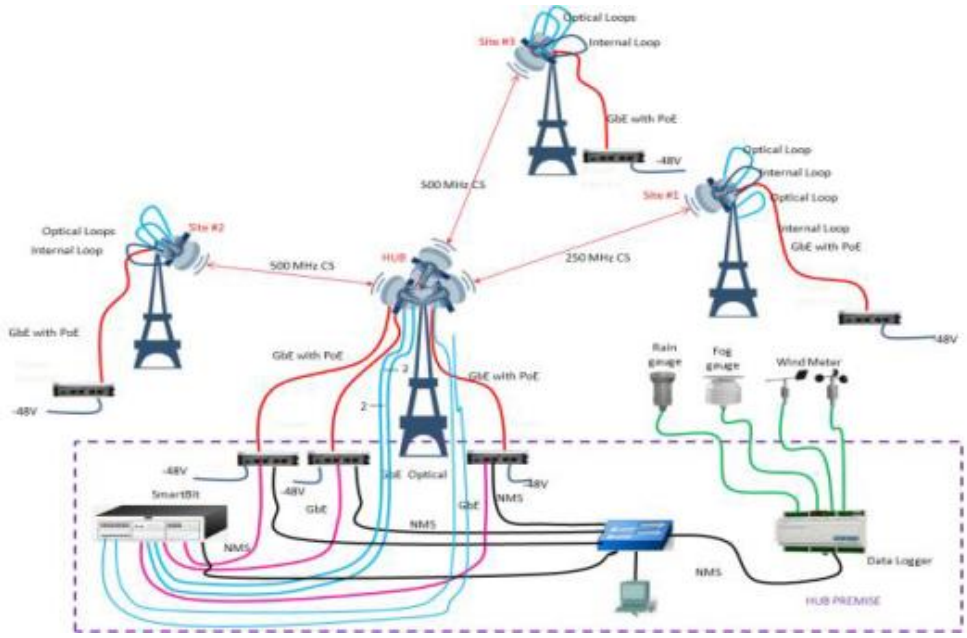
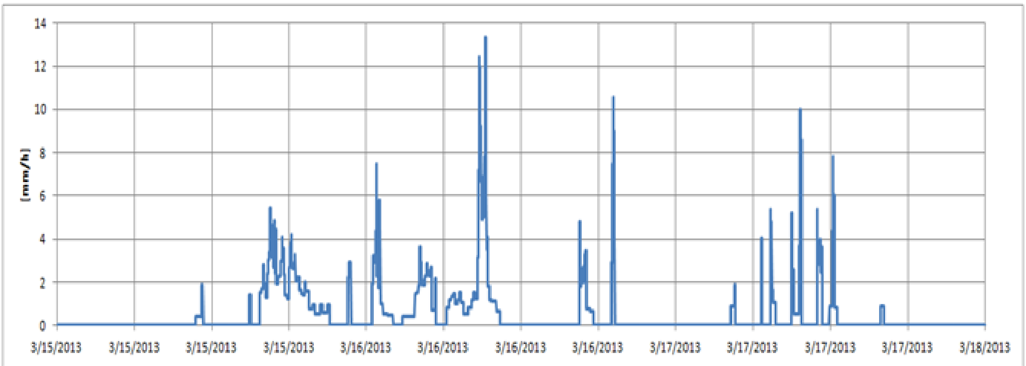


Figure 11: E-band Trial configuration

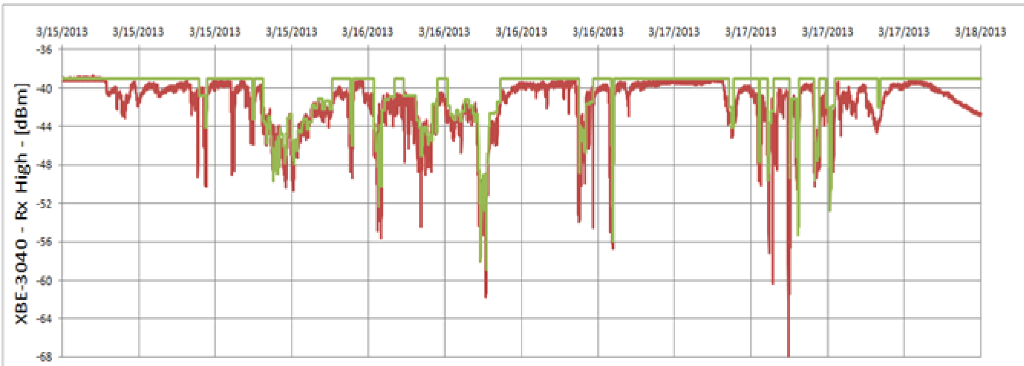
Results

Link throughput was collected using the log files provided by the packet generator. Output power, RSL, modulation format and mean squared error (MSE) were provided by the equipment itself through polling the NMS. Rain rate, temperature, humidity, wind speed and direction were provided by a weather station.

In order to make a comparison between the predicted (both with ITU-R P.530-14 [8] and ITU-R P.530-13 [7] models) and measured availability it is necessary to retrieve the rain rate statistics. Figure 12 shows an example of measured rain data, measured RSL, and predicted RSL from one of the hops.



Rain data interpolated



RSL (red line) and Rx prediction (green line) with ITU-R 530.14 model for XBE-3040 –Rx Low

Figure 12: Instantaneous rain rate and corresponding attenuation along one of the hops in the trial

Comparison between computed and measured availabilities in rain

The desktop availability estimation has been carried out by means of the following methodology and assumptions:

- The availability has been calculated by means of ITU-R P.530-14 [8] and ITU-R P.530-13 [7] models
- The instantaneous rain rate R0.01=27.5 mm/h and the rain rate integrated over 1 minute according to ITU Recommendation R0.01=21.2 mm/h

Table 3 and Table 4 show estimation and measured availabilities.

530-13								
Rain (mm/h):	21.2							
	Sub Band	64 QAM	32 QAM	16 QAM	QPSK	QPSKS 250 MHz	QPSKS 500 MHz	QPSKS 250 MHz
		Availab. %	Availab. %	Availab. %	Availab. %	Availab. %	Availab. %	Availab. %
LINK #1	Rx Low	99.9928	99.9948	99.9967	99.9985	99.999		
	Rx High	99.9828	99.9884	99.9931	99.997	99.9984		
LINK #2	Rx Low	99.9872	99.9908	99.9941	99.9972		99.9979	99.9987
	Rx High	99.9695	99.9795	99.9877	99.9946		99.9961	99.9976
LINK #3	Rx Low	99.8459	99.9133	99.9558	99.9834		99.9885	99.9934
	Rx High	99.7732	99.8781	99.9401	99.9781		99.9849	99.9913
Rain (mm/h):	27.5							
	Sub Band	64 QAM	32 QAM	16 QAM	QPSK	QPSKS 250 MHz	QPSKS 500 MHz	QPSKS 250 MHz
		Availab. %	Availab. %	Availab. %	Availab. %	Availab. %	Availab. %	Availab. %
LINK #1	Rx Low	99.9883	99.9915	99.9945	99.9973	99.9984		
	Rx High	99.9735	99.9819	99.9889	99.995	99.9972		
LINK #2	Rx Low	99.9798	99.9853	99.9904	99.9952		99.9964	99.9977
	Rx High	99.9541	99.9687	99.9809	99.9913		99.9936	99.996
LINK #3	Rx Low	99.7784	99.8732	99.9341	99.9743		99.9819	99.9893
	Rx High	99.6805	99.8254	99.9124	99.9669		99.9768	99.9864

530-14								
Rain (mm/h):	21.2							
	Sub Band	64 QAM	32 QAM	16 QAM	QPSK	QPSKS 250 MHz	QPSKS 500 MHz	QPSKS 250 MHz
		Availab. %	Availab. %	Availab. %	Availab. %	Availab. %	Availab. %	Availab. %
LINK #1	Rx Low	99.9913	99.994	99.9965	99.9988	99.999		
	Rx High	99.9796	99.9863	99.9921	99.9971	99.9988		
LINK #2	Rx Low	99.9867	99.9907	99.9943	99.9977		99.9985	99.999
	Rx High	99.9694	99.9794	99.988	99.9952		99.9969	99.9984
LINK #3	Rx Low	99.877	99.9278	99.9623	99.9861		99.9907	99.9951
	Rx High	99.8324	99.9049	99.9514	99.9824		99.9881	99.9937
Rain (mm/h):	27.5							
	Sub Band	64 QAM	32 QAM	16 QAM	QPSK	QPSKS 250 MHz	QPSKS 500 MHz	QPSKS 250 MHz
		Availab. %	Availab. %	Availab. %	Availab. %	Availab. %	Availab. %	Availab. %
LINK #1	Rx Low	99.9861	99.99	99.9938	99.9974	99.9988		
	Rx High	99.9697	99.9791	99.9874	99.9948	99.9974		
LINK #2	Rx Low	99.9795	99.9852	99.9906	99.9958		99.997	99.9984
	Rx High	99.9558	99.9695	99.9814	99.992		99.9944	99.9969
LINK #3	Rx Low	99.8325	99.8995	99.9457	99.9787		99.9852	99.9917
	Rx High	99.7764	99.8703	99.9316	99.9737		99.9817	99.9879

Table 3: Computed availabilities with instantaneous and integrated rain rates

	64QAM	32QAM	16QAM	QPSK	QPSKS (500 MHz)	QPSKS (250 MHz)
Link #1 – Rx Low	99.979	99.990	99.9959	99.9983	-	99.9989
Link #1 – Rx High	99.941	99.972	99.9839	99.9945	-	99.9976
Link #2 – Rx Low	99.907	99.974	99.990	99.9956	99.9966	99.9988
Link #2 – Rx High	99.998	99.688	99.946	99.973	99.9916	99.9948
Link #3 – Rx Low	98.375	99.860	99.948	99.9933	99.9990	99.9998
Link #3 – Rx High	98.380	99.535	99.813	99.964	99.9859	99.9998

Table 4: On-field measured availabilities

Comparison between measured and predicted attenuation in fog

Estimation of the fog density during the two events:

- The first fog event density: (5.25 – 4.6)=0.65 g/m3
- The second fog event density: (5.00 – 4.79)=0.21 g/m3

Based on the estimation, the ITU-R model was used to predict attenuation due to fog over the three hops. The results are summarized in Table 5.

FOG EVENT ON FEBRUARY 17th			
HOP	Attenuation due to Fog [dB]	Estimated RSL [dBm]	Minimum Measured RSL [dBm]
LINK#1	5.7	-43.7	-45.5
LINK#2	6.8	-43.8	-42.2
LINK#3	8.9	-53.4	-51.5

FOG EVENT ON FEBRUARY 18th			
HOP	Attenuation due to Fog [dB]	Estimated RSL [dBm]	Minimum Measured RSL [dBm]
LINK#1	2.6	-41.6	-43.4
LINK#2	3.1	-40.1	-40.4
LINK#3	4.0	-48.5	-49.5

Table 5: Comparison between measured and estimated RSL during fog events

Conclusions

By comparing the results the following conclusions can be made:

- The E-Band technology has been tested successfully in-field
- As it was already clear both from the preliminary link budgets and previous chapters, the models in ITU-R P.530-13 [7] and ITU-R P.530-14 [8] are very similar.
- The availabilities estimated with measured rain rates are better than those estimated in the link budgets. This is because link budgets were carried out by using the rain rate provided by ITU for the trial's region (R0.01=35 mm/h).
- It is possible to observe that, for a given rain rate, ITU-R P.530-13 [7] estimates higher availability (with respect to ITU-R P.530-14 [8]) in case of small fading margin (e.g. higher modulation formats) while it estimates lower availability in case of high fading margin (e.g. QPSK).
- If we compare the estimated availabilities (with measured rain rates) with those measured in field, we can see that the rain rate that allows better predictions is the instantaneous one. That means that the two models overestimate the availability of the links if the integrated rain rate R0.01 is used.
- If we consider the instantaneous rain rate, the estimated availabilities made by using ITU-R P.530-14 [8] are closer to the availabilities measured on field.

Availability predictions in Turin

This trial is reported by Telecom Italia and Huawei.

Scope

The trial had the aim to characterize the use of E-band, through the collection of radio data performance and throughput related to the weather conditions. The trial has been developed during the period from 5 June to 31 October 2013, at Telecom Italy Turin premises.

Setup

The rainfall log data are available from a weather station, with a resolution of 10 minutes, and the radio link object of the experiment is a commercial E-band radio in a full outdoor installation with adaptive modulation up to 64QAM.

In order to compare system performances with a traditional band installation, we used as a benchmark a different installation that is in service in different sites close to the trial sites. This benchmark system is an in-field installation operating in the range of 18 GHz.

Figure 13 shows the location of the E-band link (blue line), the benchmark link (red line) and some link characteristics.

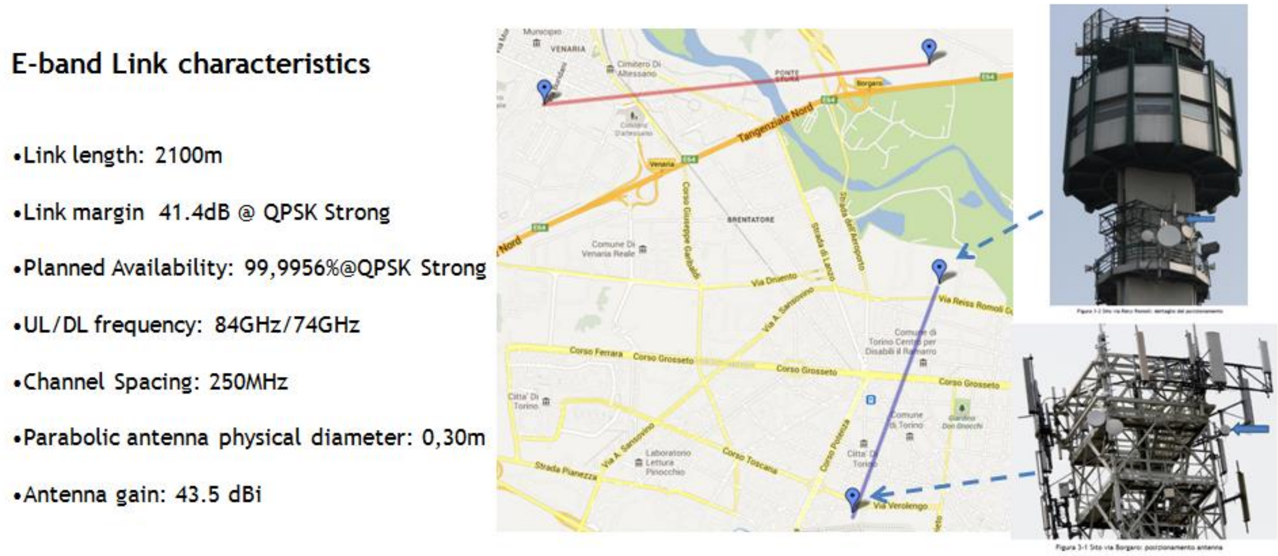


Figure 13: Link characteristics and location.

This is a full outdoor installation with reduced footprint and small parabolic antenna size (30cm). This size of antenna is suitable for dense urban environments because it simplifies alignment procedure and improves system camouflage. In the E-band frequency range the gain of this antenna is sufficient to fit urban applications.

Results

Rain attenuation

The measured values have been grouped by rainfall and compared with data obtained from the model given in Recommendation ITU-R P.838-3 [6] and are shown in Figure 14 and Figure 15. Thus it is possible to calculate the expected attenuation as a function of rainfall at different carrier frequencies.

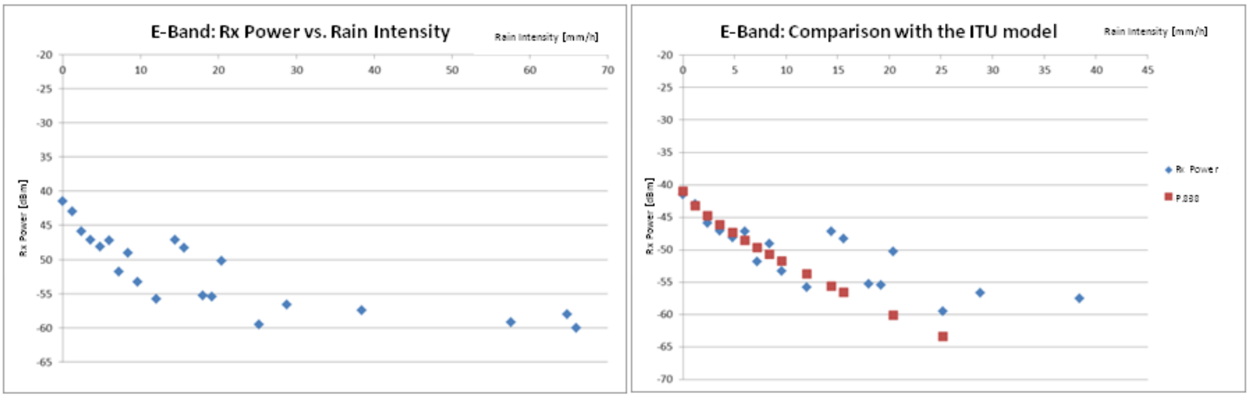


Figure 14: E-band system rainfall class vs. Rx power

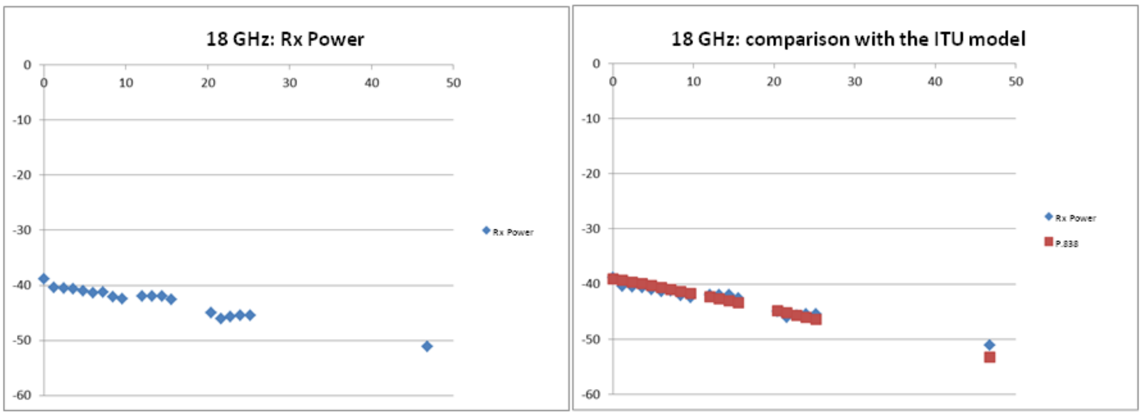


Figure 15: Benchmark system rainfall class vs. Rx power

The following observations are made:

- The results of measurements at 18GHz are in good agreement with the P.838-3 Recommendation.
- Some samples at 80GHz have been removed from the comparison model. Particular samples of E-band attenuation seem overestimated by the Recommendation (few dBs) compared to the values of the band at 18 GHz that are completely overlapped with those estimated by the theoretical model.
- The discrepancy observed in some classes could be due to the low number of samples detected and to the resolution of the weather station (10 min), different from the Rx Power measurement (1 minute).

Attenuation at dry day and thunderstorm events

In the following graphs, different intraday events are reported, i.e. no rain and thunderstorm events. Figure 16 shows the Rx Power samples of the E-band system (1 sample/min) during 24 hours (24x60=1440 values/day) in a dry day. Figure 17 shows the evolution of the Rx Power during thunderstorms. The benchmark system is also shown.

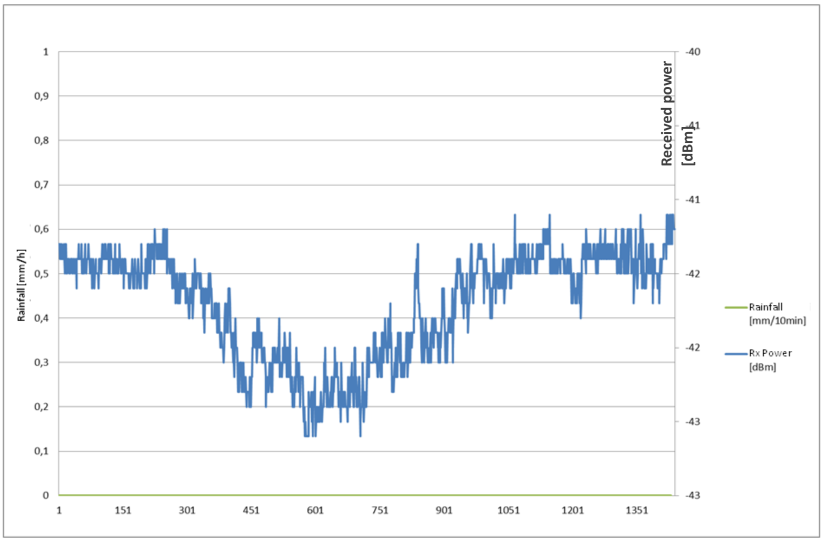


Figure 16: No rain events, E band system in normal operation

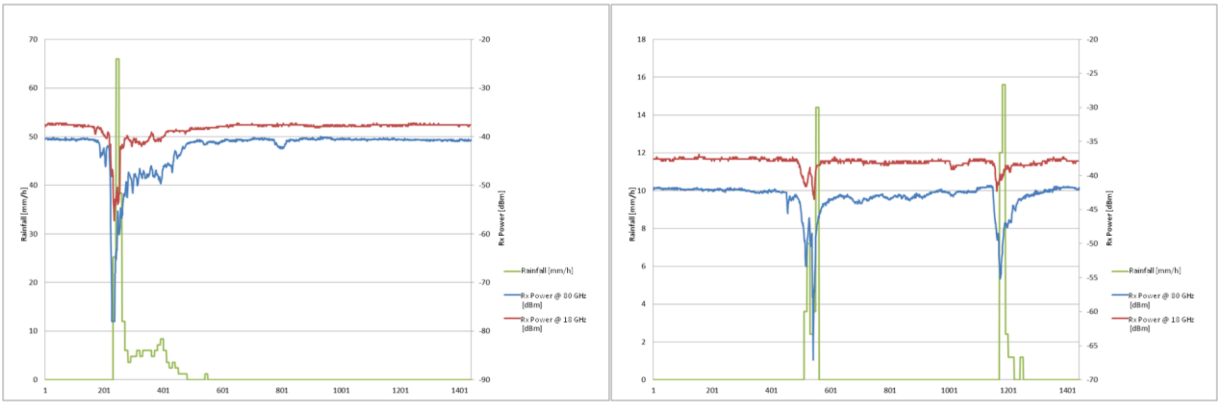


Figure 17: Thunderstorm events

Conclusions

The trial had as main objectives to verify the operation of an E-band radio (71-86 GHz) and compare the in-field results with theoretical values and benchmark results.

The results are very close with the expected values, even though in some cases the characterization requires a greater number of samples to mitigate the differences observed with respect to the theoretical models.

This experience with the E-band was performed with a system with adaptive modulation up to 64QAM to verify the impact on the dynamics of the received power and the expected availability of the link.

It is important to highlight that the trial has substantially confirmed the theoretical calculation model of rain fading at 18 GHz, definitely verified by many authors. Despite some slight differences, the model ITU-R P.838-3 [6] can also be used to capture the fading in E-band. We had however a slightly lower availability to measurement data due to the limited observation period.

E-band radio performance with ACM

This trial is reported by NEC.

Scope

A trial was conducted to evaluate E-band mm-wave point-to-point radio in Japan during the period 27 February to 20 March 2015. The objective of the trial was to verify E-band radio performance with Adaptive Coding and Modulation (ACM).

Setup

The trial was set up with a link onshore in Japan with a distance of 2.65km as illustrated in the Google map in Figure 18.

Figure 18: Geographical locations of the two test links.

The site configurations in the map shown above are summarized as follows.

Site A:

- Altitude : 3.5m
- Height of Building : 34m
- Antenna Pole : 2.4m
- Antenna Elevation :-0.98°

Site B:

- Altitude : 14.2m
- Height of Building : 10m
- Antenna Pole : 2.4m
- Antenna Elevation : 0.98°

A frequency division duplexing (FDD) scheme is used with the following duplexing frequencies, maximum and minimum transmission power and antenna sizes at both sites. The channel spacing is 500MHz.

	Site A	Site B
Tx Freq.	75.375GHz	85.375GHz
Tx PWR	+18dBm max +9dBm min	+18dBm max +9dBm min
Antenna	Φ30cm（43dBi）	Φ30cm（43dBi)

Table 6: Link configuration – Centre Frequencies, transmission power and antenna used in the trial

The maximum capacity of the link is 3.2Gbps and prioritised data traffic of 800Mbps + 1Gbps was configured. The trial measured the maximum and minimum RSL for a period of 15 minutes as well as the selected ACM and its corresponding throughput.

Results

Samples of the measured data are shown in the Figure 19 Figure 19: Example of Measured Data at Site A. below at node A. The data captures the propagation link conditions such as temperature, rain intensity and wind. It also records the maximum and minimum RSL and is compared with the calculated RSL value. The operational ACM mode modulation is also recorded together with the corresponding packet loss rate (PLR).

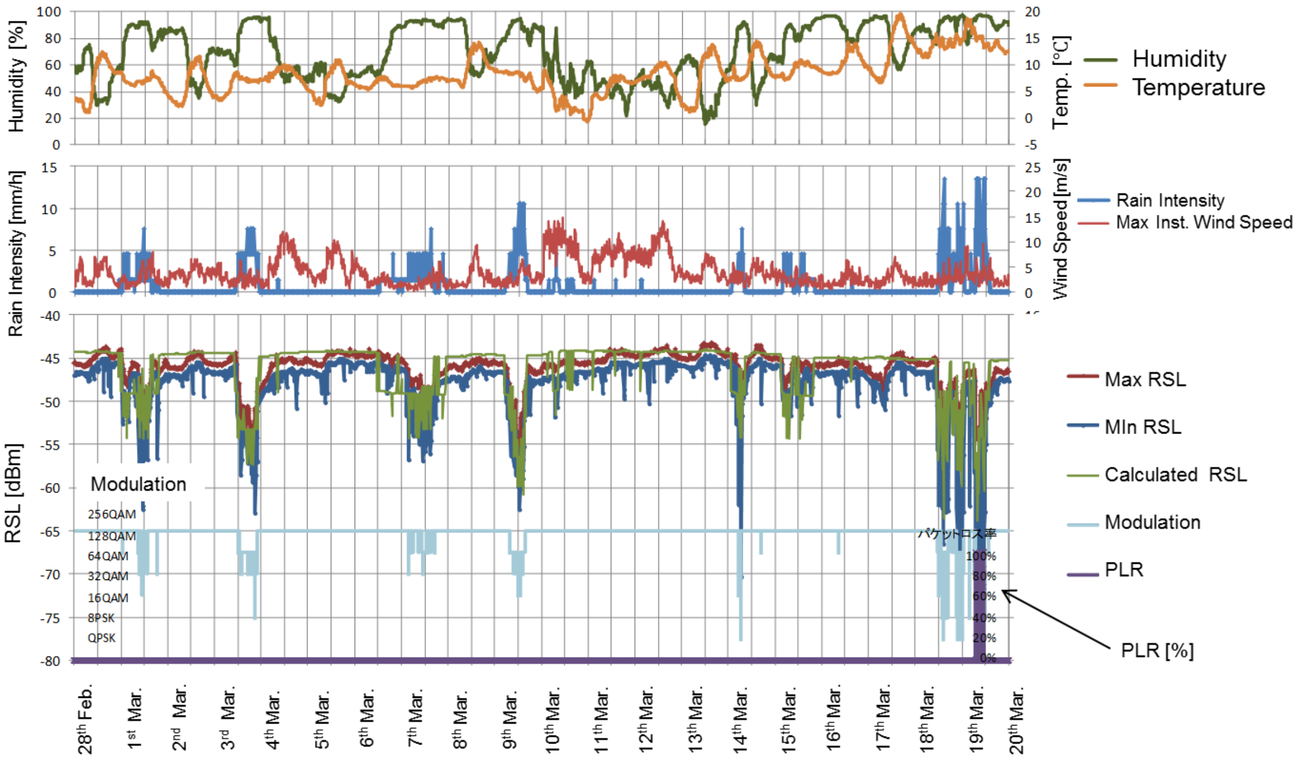


Figure 19: Example of Measured Data at Site A.

Conclusions

During the trial, the measurement results revealed that the flat fading margin was critical for 256QAM as this ACM mode was not available on the link from node B to node A; however, it was available on the link from node A to node B.

By zooming in to the fading event as shown in Figure 20 below, we see the cause of outage is due to fading during rainfall. During this period, the observed RSL value appears to be lower than expected according to the rain rate condition. This indicates that there is another factor causing additional fading. This could be due to a building near the path that might be reflecting the beam and causing this unexpected additional fading condition.

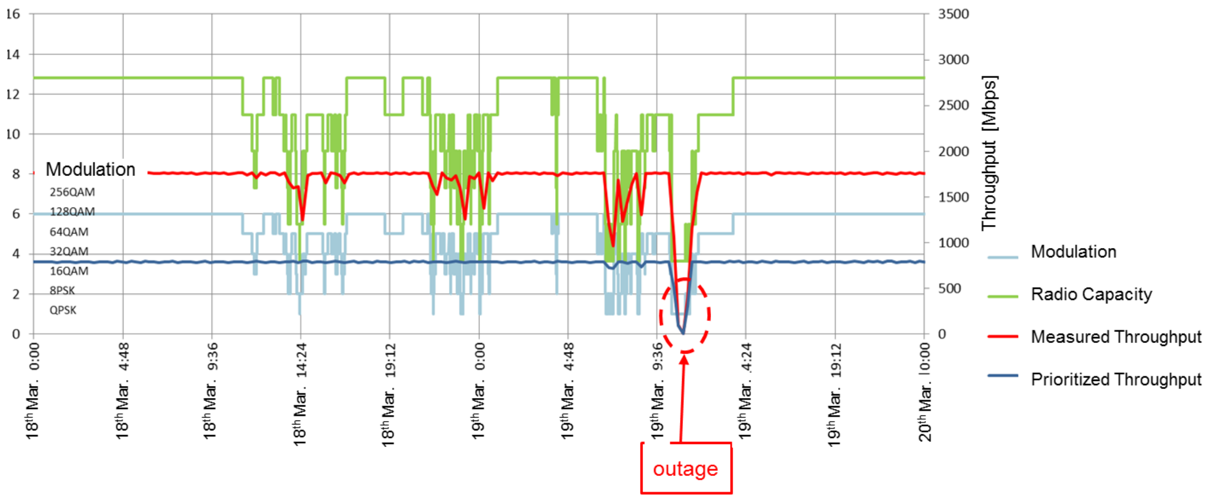


Figure 20: Detail view of fading event

Detailed analysis of the ACM modes utilisation is shown in Figure 21. Overall, the trial demonstrated that prioritised throughput was maintained even during switching between ACM modes. As such the operation and ACM in the E-band are proven to be effective.

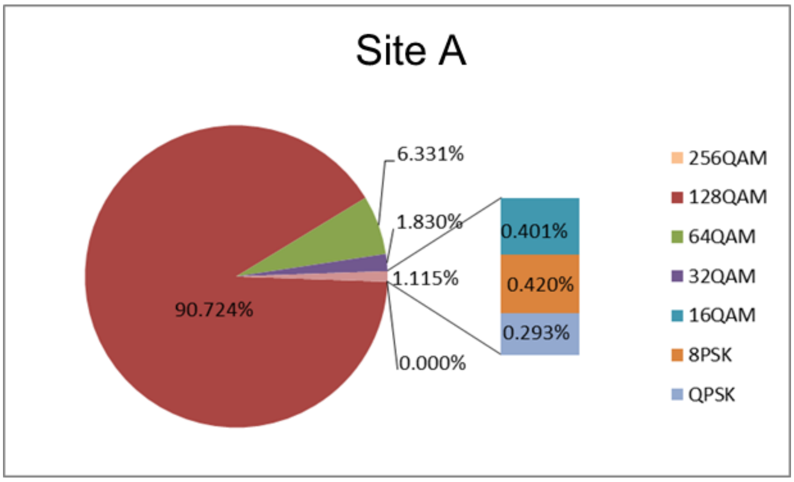


Figure 21: ACM modes usage profile from the trial

E-band radio performance for a 10+ km link

This trial is reported by NEC.

Scope

A trial was conducted in Japan in March and April of 2015 for a Point to Point radio link with a hop length of over 10km operating in the E-band.

The purpose of the trial was to evaluate the performance of a Point to Point radio link in the E-band with hop length of over 10km.

Setup

The trial was setup with a link onshore in Japan with a distance of 12.2km as illustrated in the Google map below, Figure 22.

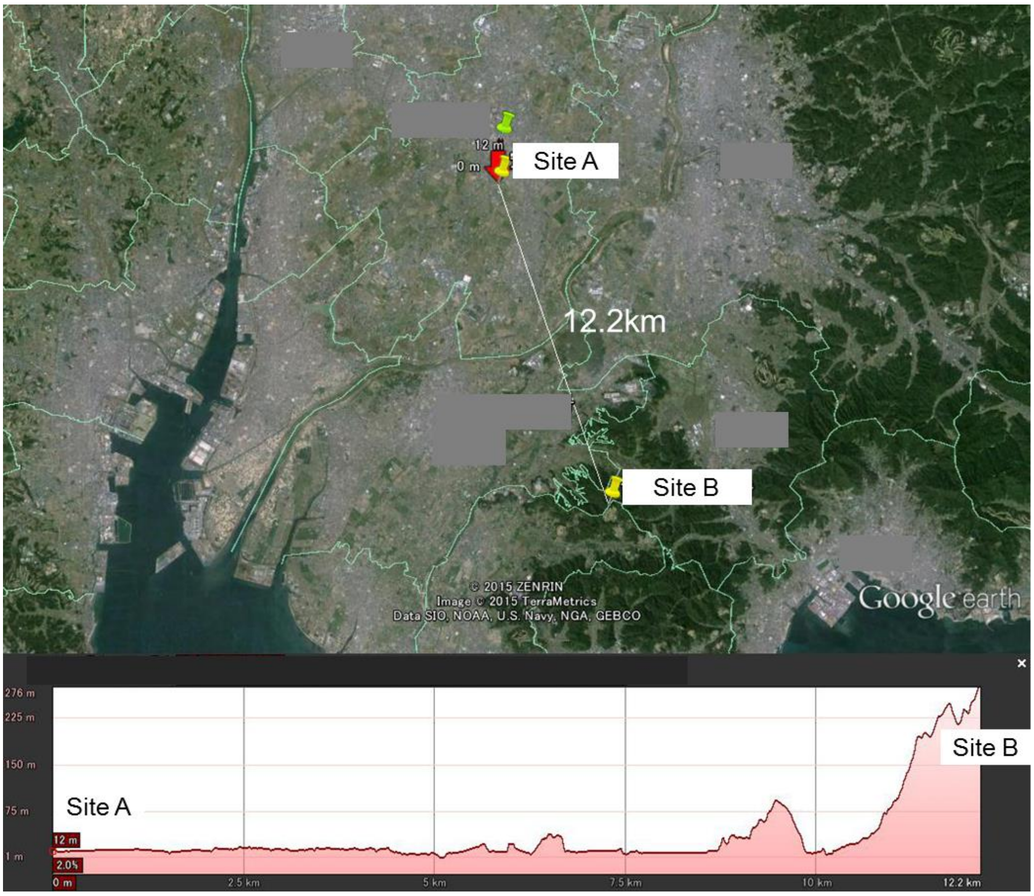


Figure 22: Geographical locations of the two sites with heights profile of the link

The site configurations in the map shown in Figure 22 are summarized as follows:

- Because of the long hop length (relative to typical mm-wave radio) of 12.2km, the modulation was fixed to QPSK as the most robust ACM mode.
- The duplexing scheme used in the trial is FDD with 500MHz channel bandwidth.
- The calculated required RSL threshold at the E-band is -69dBm at bit error rate (BER) of 10^{-6}. The maximum capacity for the link at this ACM mode is 780Mbps with packet size fixed at 1518 bytes.
- The trial was conducted with 2 different maximum transmission powers of 18dBm and 12dBm. These are designated as setup ① and setup ②.
- Trial setup ① was conducted from 15 to 27 March 2015. Trial setup ② was conducted between 27 March and 10 April 2015.

The centre frequencies, transmission power and antenna gain used for each setup are summarised in Table 7 below.

	Site A	Site B
Tx Freq.	75.375GHz	85.375GHz
Tx PWR	①+18dBm ②+12dBm	①+18dBm ②+12dBm
Antenna	Φ60cm（50dBi）	Φ30cm（43dBi）

Table 7: Link configuration – Centre Frequencies, transmission power and antenna used in the trial

Results

During the trial, measurements for maximum and minimum RSL values as well as Error Second (ES) and Unavailable Seconds (UAS) were recorded every 15 minutes for each of the setups. In addition, Packet Loss Rate (PLR) was recorded at 30 seconds intervals.

Samples of the measured data are shown in Figure 23 and Figure 24 for both setups ① and ② respectively together with the recorded wind speed (m/s), water vapour (g/m^3) and rain intensity (mm/h).

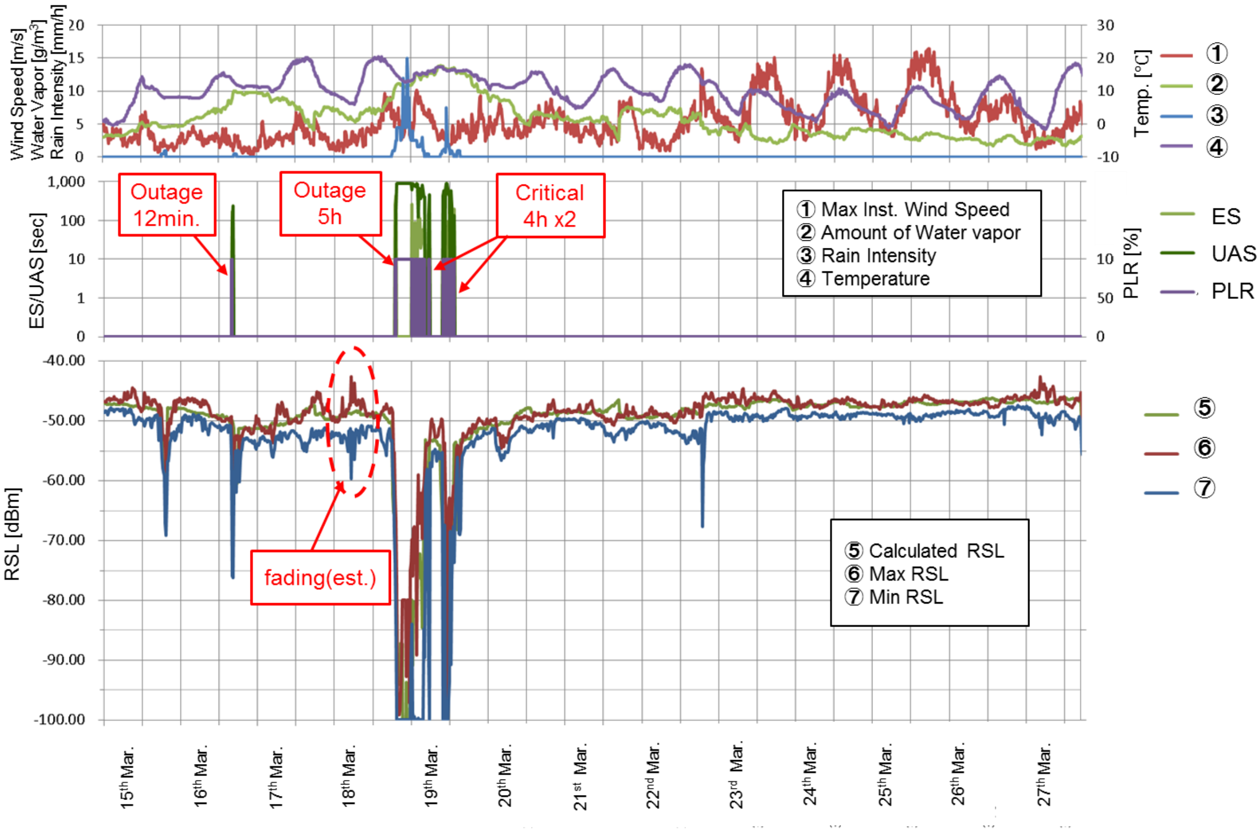


Figure 23: samples of measured data at Site A with setup ① (+18dBm Tx power).

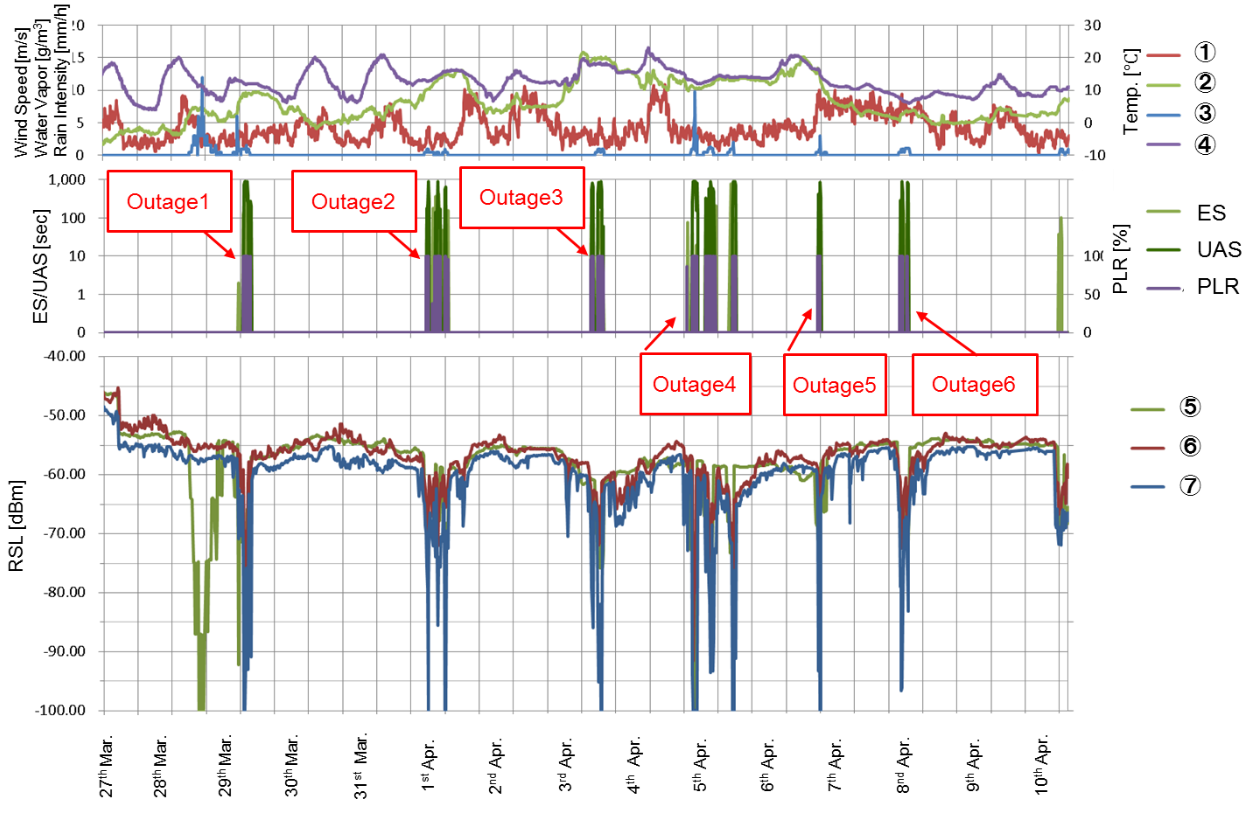


Figure 24: Sample of measured data at Site A for setup ② (+12dBm Tx power).

Conclusions

The trial results showed good link performance in clear sky conditions, i.e. no rain, for both setups. However, the link with setup ② of lower Tx power turned out to be more sensitive to rain even in light rain rate conditions. Setup ① with higher Tx power is proven to be more tolerant to rain with less outage. Table 8 summarises the achieved outage durations and availability at each node for both transmission power setups.

	Site A	Site B
UAS	①35128sec ②32167sec	①17551sec ②17551sec
Availability	①96.8% ②97.3%	①97.3% ②98.5%

Table 8: Outage results and availability

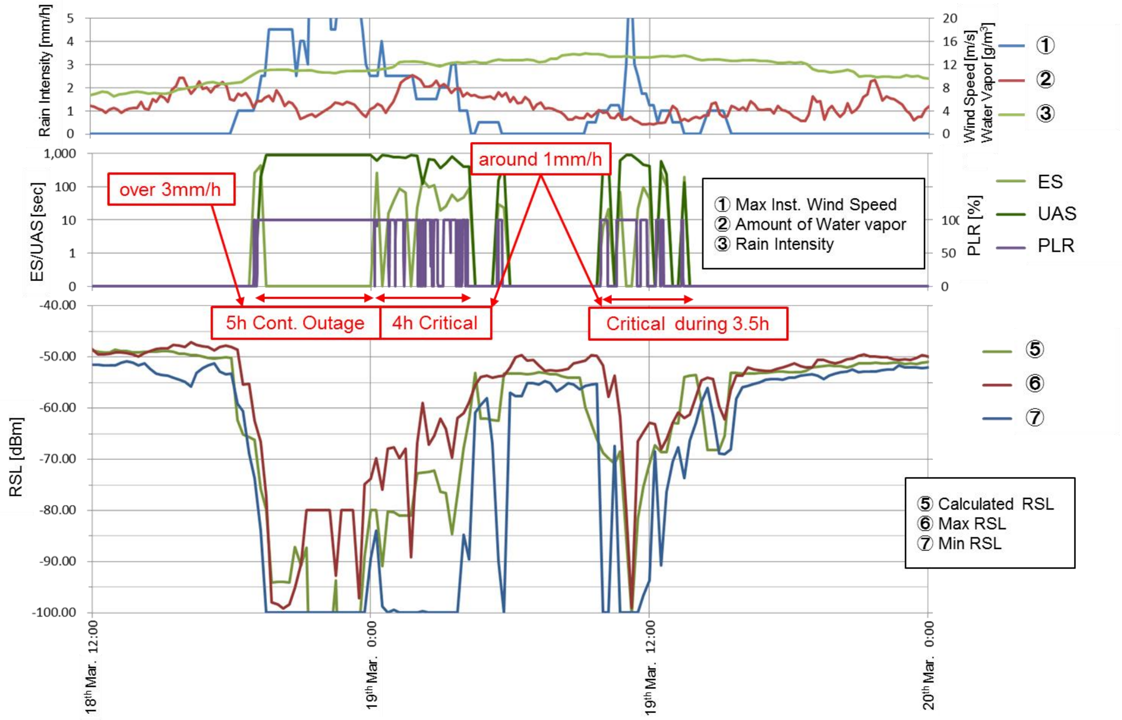


Figure 25: Detailed view of outage and critical conditions events from Figure 23.

Detailed and zoomed in view of the fading events for setup ① is shown in Figure 25.

In summary, the measured maximum RSL was consistent with the estimated values by calculation. There was no outage observed under good weather conditions (clear sky). It was confirmed that at such a long hop length link operating in the E-band, outage is inevitable at rain rate of 3mm/h or higher and a critical condition of the link is expected at a rainfall of 1mm/h.

Monsoon trials in India

This trial is reported by Siklu.

Scope

An Indian operator trialled E-band links (1ft antenna) during the monsoon season in Mumbai. The operator required:

- Ease of installation
- High capacity
- Small footprint (most links deployed on rooftops)
- Interference free band
- 99.95% availability target for the highest capacity (1000Mbps).

Setup

Two links were installed, a 750m link and a 1400m link. The link supported 5 levels of hitless adaptive modulation schemes and the E-band radio performance was monitored and correlated with weather statistics. The monitoring took place for an entire monsoon season in Mumbai (3 months), the monsoon in that region is one of the harshest in India, and the 2011 season was particularly challenging. Planning included utilization of Siklu's link-budget-calculator, loaded with both system specifications and ITU-R rain zones database.

Weather report

"The city (Mumbai) has received about 90 per cent of its average annual rainfall and a month of monsoon is still left, according to data recorded at the automated weather stations installed at 34 locations across the city". Mon 29 Aug, 2011, 01:32 hrs

Results

The E-band radio performance was monitored and correlated with weather statistics and the experienced availability was as expected according to link budget calculations and rain statistics. Figure 26 shows the measured availability and rain rate. Rain fade was as predicted by ITU-R models.

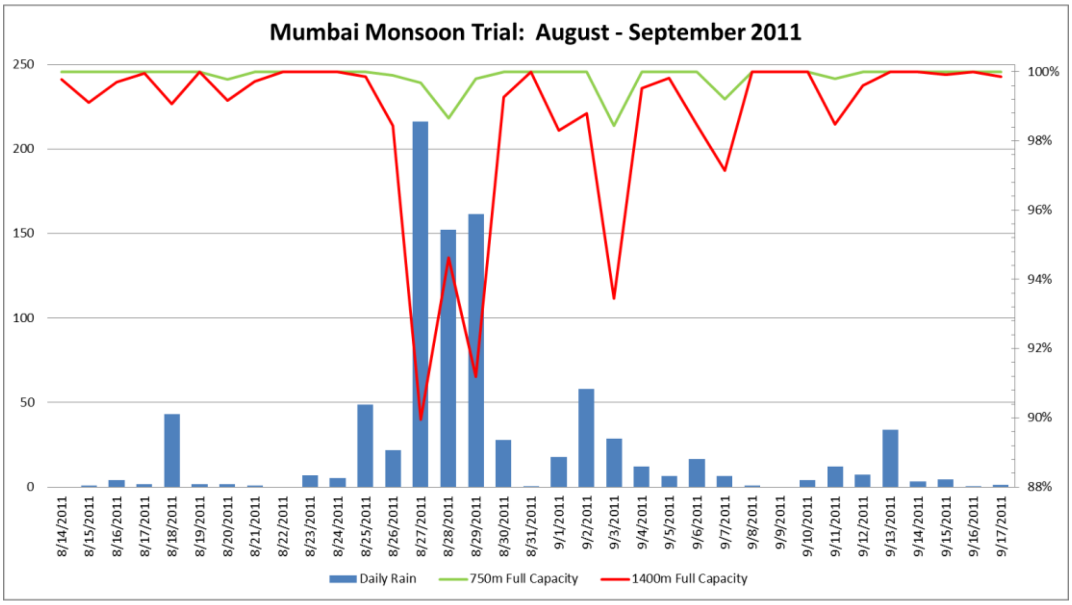


Figure 26: Correlated Rain mm/h [blue, left axis], Link per-day availability [green, red, right axis]

Conclusions

- Actual performance matched the design goals, keeping ≥90% daily availability for the 1400m link and ≥98% daily availability for the 750m link, even at the season's heaviest rains periods.
- Fade margin values used during planning phase with the link-budget-calculator proved to deliver reliable availability, as well as capacity.
- The operator concluded: "It is possible to deploy 1ft E-band links for 800-1200 meters distances"

V-band field experience

In this chapter experience from independent trials with more non-conventional deployments using V-band is described. The trials have been conducted by members of the ETSI ISG mWT and the contributors, including their contact details, are listed in the list of authors.

Summary of V-band field experience

The V-band trials, including more non-traditional street-level deployments, are reported. V-band is characterized by oxygen absorption and unlicensed spectrum making it more suitable for shorter links. Furthermore, it is difficult to predict performance in Non-Line-of-Sight (NLOS) deployments where the link relies on reflections and/or diffractions that are difficult to plan for. However, the reported V-band trials show good performance when deployed properly.

Availability predictions in Newbury, UK

This trial is reported by Vodafone and Ericsson.

Scope

The aim of the trial was to investigate the performance of V-Band technology and in particular to measure the availability.

Setup

The trial was performed using two links (with 50MHz channel spacing and modulation from 4QAM up to 256QAM) from a building roof top to perimeter road lamp posts. Link 1 had a length of 273m and Link 2 had a length of 64m. The far end units were mounted at the top of the lamp posts to give a clear line of sight. Figure 27 illustrates the setup.

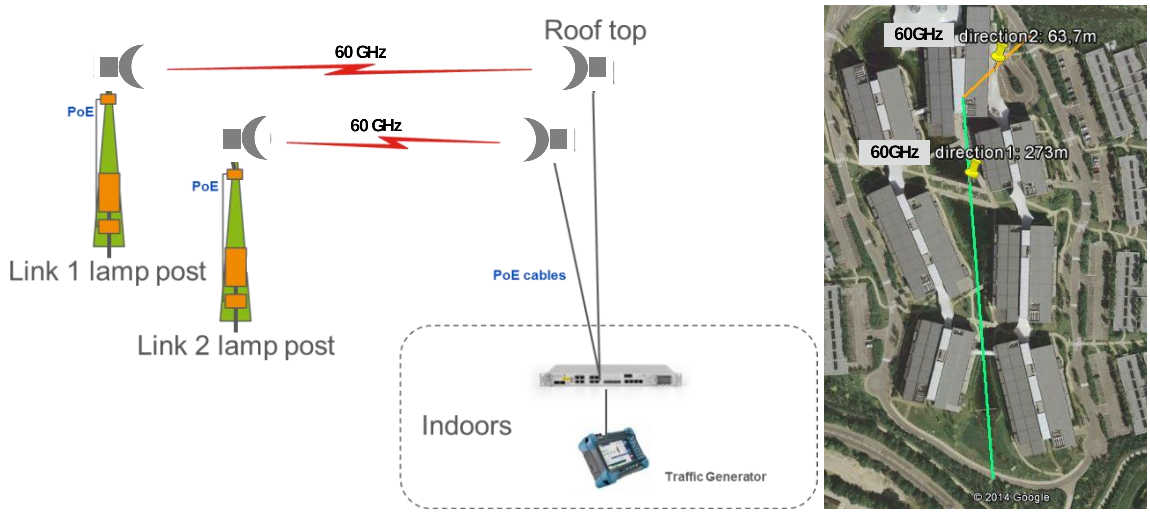


Figure 27: Trial setup

Results

Link throughput, Rx levels, modulation levels and weather data were logged for 50½ days in total during two periods:

- Period 1: 14/08/14 to 05/09/14.

* Period 2: 25/09/14 to 23/10/14.

Due to remote access difficulties, data logs were not taken during the very dry period from 5 to 25 September when link performance was at maximum.

The throughput and availability over the two measurement periods for each modulation level are found in Table 9 and it can be seen that a high performance is achieved on both links. The long link 1 achieves 5 nines availability at 64 QAM 279.0 Mbps, with an average throughput over the period of 367.3 Mbps. The short link 2 achieves nearly 6 nines availability at 256 QAM 367.8 Mbps.

LINK 1 (273m)	4QAM	16QAM	32QAM	64QAM	128QAM	256QAM
Data Rate (Mbps)	94.708	187.266	233.561	279.040	323.793	367.838
Seconds at Modulation	0	2	52	559	49874	4318098
Availability	100.0000%	100.0000%	100.0000%	99.9988%	99.9860%	98.8443%
LINK 2 (64m)	4QAM	16QAM	32QAM	64QAM	128QAM	256QAM
Data Rate (Mbps)	94.708	187.266	233.561	279.040	323.793	367.838
Seconds at Modulation	0	0	0	2	8	4368551
Availability	100.0000%	100.0000%	100.0000%	100.0000%	100.0000%	99.9998%

Table 9: Throughput and availability

Figure 28 shows correlation between rain rate, wind and Rx levels. For the longer link 1 there is a clear correlation between rainfall, Rx levels and throughput. Raindrop size, wind speed and direction also change the effects of the rainfall. The link performance was also reduced during a period of fog when the humidity was 97% and showed higher than normal sensitivity to the rain. This may have been due to water on the radome and/or absorption by the fog.

Some significant wind effects were observed on link 2, but this was caused by branches on the trees next to the far end transmitter blowing across the line of sight during gusty high wind conditions. However this did not significantly affect the link availability or throughput.

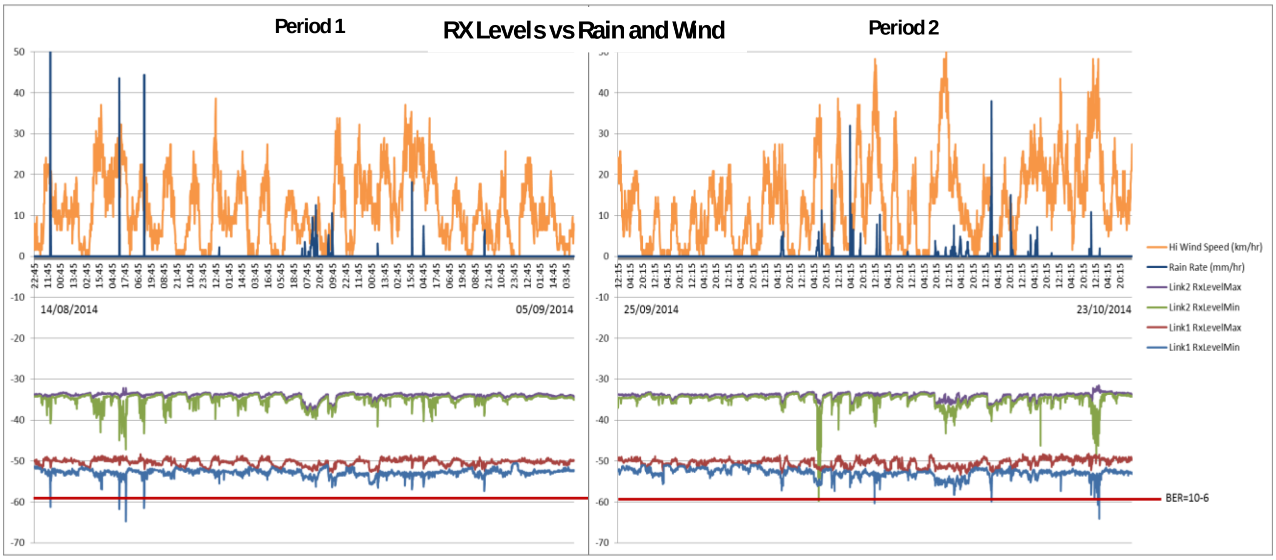


Figure 28: Correlation between rain rate and wind levels with the Rx levels

Table 10 shows a comparison between predicted and measured availability. Using the Adaptive Modulation thresholds and wet radome with 3dB loss gives a close match to the measured results.

	Planning ITU-R P.530-14				
	Fixed Modulation 256 QAM		Adaptive Modulation 256 QAM		
	Dry Radome	Wet Radome	Dry Radome	Wet Radome	Measured
Link 1 (273m) Availability	99.9958%	99.9694%	99.98954%	99.86024%	98.8443%
Link 2 (64m) Availability	100.0000%	100.0000%	-	-	99.9998%

Table 10: Predicted and measured availability

Availability predictions are compared to the measurements and there is a close match between the prediction using adaptive modulation switching threshold and the measured results. However a dry period during September was excluded from the results and the measurement period is not long enough to draw any significant conclusion about the accuracy of the ITU-R models.

Conclusions

When using V-band the following recommendations can be made:

- For link planning use ITU-R P.530-14 [8] or later.
- When using Adaptive Modulation use the switching thresholds in the planning calculations.
- During planning allow additional fade margin and take a generally cautious approach due to effects of:
    - Surface water on the Radome (e.g. 3dB loss)
    - Humidity/Fog
    - Wind
    - Snow
- 1st Fresnel zone should be clear of obstructions, with care taken to ensure that trees or plants cannot blow across the zone in strong gales.
- Ensure that the lamp post provides sufficient rigidity at the mounting height to prevent the antenna from moving significantly and do not block lighting.
- Check for interference sources using a frequency scan of the band. Note that a narrow beam high gain antenna will provide significantly more protection against other unlicensed sources which may be installed in the future.

Characterization of V-band through measurements

This trial is reported by Telecom Italia and Ericsson.

Scope

The trial has the aim to characterize the use of V-band through the collection of radio data performance and throughput related to the weather conditions. The rainfall log data are available from a weather station with a resolution of one minute.

Setup

The radio link object of the experiment is a full outdoor installation with adaptive modulation up to 64QAM. The trial was performed at the Telecom Italy Turin premises during November 2014. Figure 29 shows the location of the V-band link.

Figure 29: V-band link location.

This was a full outdoor installation with reduced footprint and a spherical antenna (20cm). This size of antenna is suitable for dense urban environment because it simplifies alignment procedure via a dedicated camera and telephone app. This configuration enables an effective system camouflage. In the V-band frequency range the gain of this antenna is sufficient to compensate oxygen absorption peak and fit service extension applications.

Results

The measured values have been grouped by rainfall and compared with data obtained from the model given in Recommendation ITU-R P.838-3 [6]. Thus it is possible to calculate the expected attenuation as a function of rainfall at different carrier frequencies. Figure 30 shows the measured rain attenuation compared to model predictions.

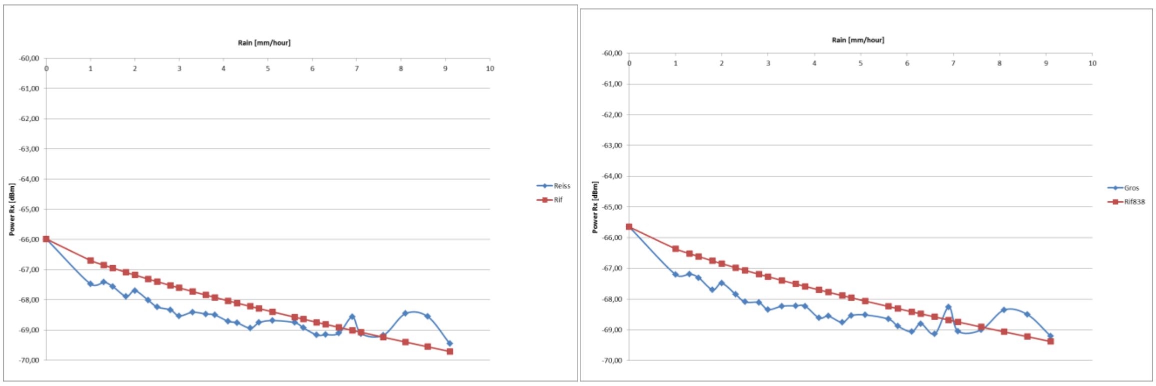


Figure 30: V-band Rx power vs Rain rate.

Some samples at 60GHz were removed from the comparison model. V-band rain attenuation seems underestimated (a few dBs) by the Recommendation. The discrepancy observed in some rain classes could be due to the low number of samples detected. Another issue is the link length which is too long for a typical V-band application. This length was adopted just to stress performance of the equipment.

In the following graphs, different intraday events are reported, i.e. no rain events and thunderstorm events. Figure 31 shows the Rx power samples of the V-band system (1 sample/min) during 24 hours (24x60=1440 values/day) of a dry day. Figure 32 represents the evolution of the Rx power during a rainy day.

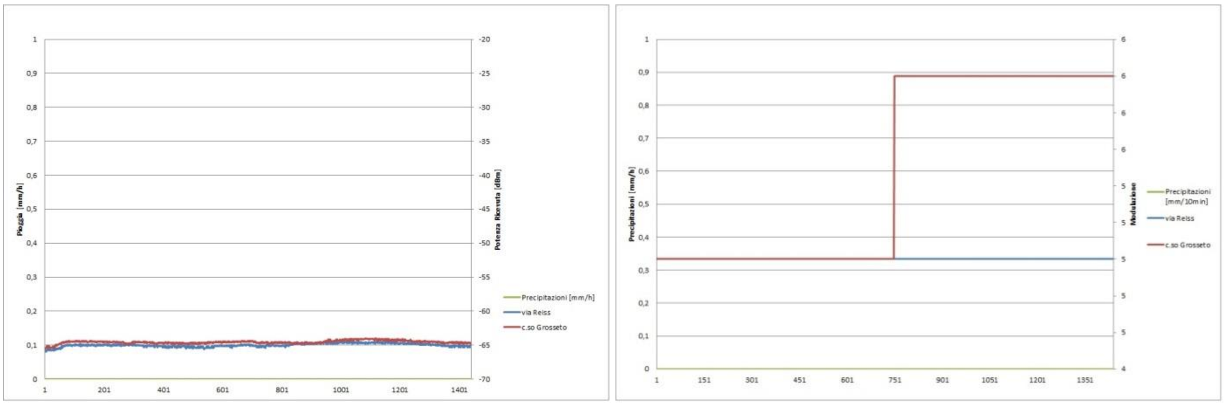


Figure 31: No rain events, V-band system in normal operation

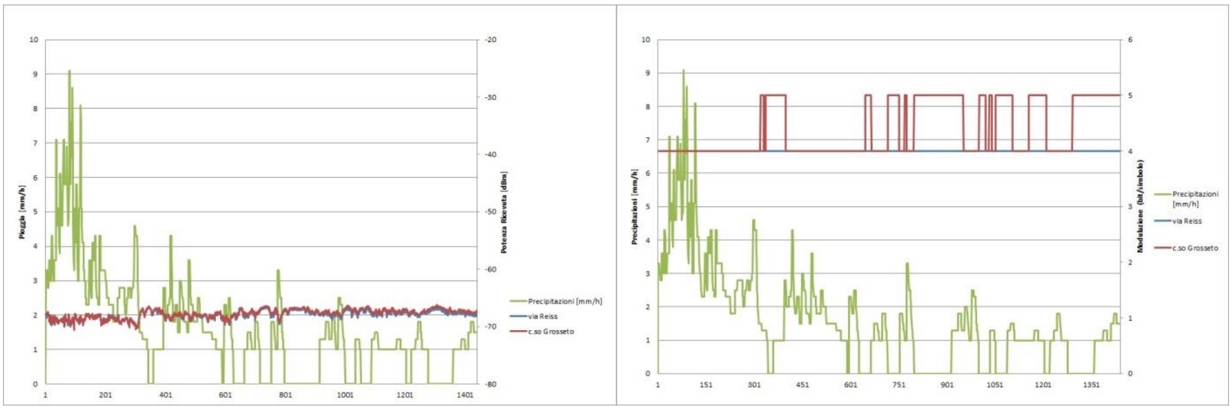


Figure 32: Daily continuous rain event

Conclusions

The main objectives of the trial were to verify the operation of a V-band radio (57-64 GHz) and compare the on-field results with theoretical values and benchmark results.

The results are very close to the expected values, even though in some cases the characterization requires a greater number of samples to mitigate the differences observed with respect to the theoretical models. It is however important to highlight that the trial has substantially confirmed the theoretical calculation model of the rain fading.

V-band trials in Bristol, UK

This trial is reported by EE and NEC.

Scope

A trial was conducted by EE for mm-wave equipment operating in the 60GHz band (V-band). The trial took place in the period from 7 November 2012 to 11 August 2013. The trial used Point-to-Point radio operating in the 60GHz band and took place between two EE offices in Bristol, England, UK.

The objective of the trial was to evaluate the street level performance of V-band. Street level deployment was not possible at the time. The link was installed between two sites with the raised roof in between that emulate street level.

Setup

The radio link for the trial was setup using NEC early prototype PtP radio operating in the 60GHz band with the following parameters and settings

- Frequency band: 59 – 63GHz
- Modulation: QPSK to 256QAM fixed at 16QAM for the trial
- Output power: max -2dBm(16QAM), min -17dBm (fixed at -2dBm during trial)
- Channel BW: 50 MHz
- Antenna Gain: 33dBi
- Antenna Beamwidth: 3deg

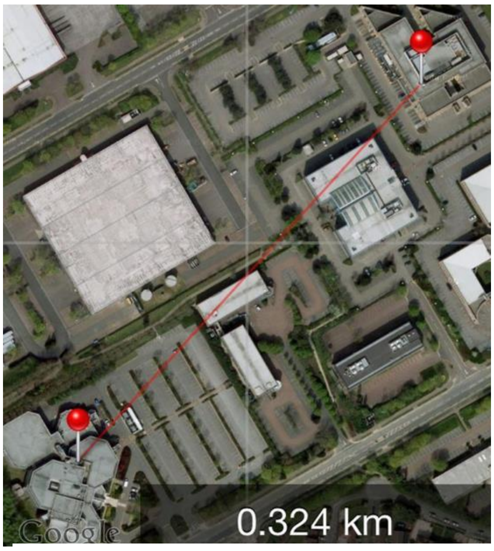
Figure 33: Equipment used in the trial

The trial took place at EE offices in Bristol between Parkgate and Aztek in the city of Bristol, UK.

The link is installed between two sites as illustrated in the photo shown in Parkgate (AVN0145 top right), and Aztec 800 (AVN0151, bottom left).

The link path passes directly over a flat roof, near the Parkgate site, which should provide similar transmission characteristics to a street level deployment, with multiple reflections from an essentially flat surface, relatively close to the radio. There are also a number of minor beam obstructions such as railings, which again fairly closely simulate potential mounting scenarios.

These locations do not provide an opportunity to fully simulate a street canyon environment, and given the limited distances achievable with equipment in the 60GHz band, alternative sites around the Bristol campus have not been located. It does however allow testing of general transmission characteristics, assessment of the ease of installation etc.



Location of the trial

The equipment was initially installed during the week commencing 15 October and the following performance was recorded at the commissioning time.

- The calculated RSL for the link is -58.5dBm. On the day of installation the actual RSL at Parkgate was an indicated -60.9dBm (-2.7dB) and at Aztec 800 it was an indicated -61.3dBm (-3.1dB).

- The measured layer 2 throughput during installation was 182.63Mb/s when operating at 16QAM (max expected is 200Mb/s including overhead)

- The claimed “typical” threshold limits are -73dBm for QPSK and -67dBm for 16QAM. Note that this prototype equipment does not include Adaptive Modulation, so the link is fixed at 16QAM at present.

- During installation both ends of the link were measured with the far end muted, and gave an indicated -99dBm. This is indicative of both an interference free installation, and a good dynamic range on the RSL meter.

Throughout testing, weather data (primarily rain rate in mm/hr) has been collected from a local weather site and in the event of notable events, rain correlated back to the performance data. We capture both overall mm, and peak mm/hr rain rate. The graph in Figure 34 shows the daily max rates (mm/hr) since the system was deployed.

Additional data such as wind direction, temperature etc. is available to download at the same site, should it prove necessary to analyse radio events in more detail. This data is also imported onto RSL graphs to show correlation.

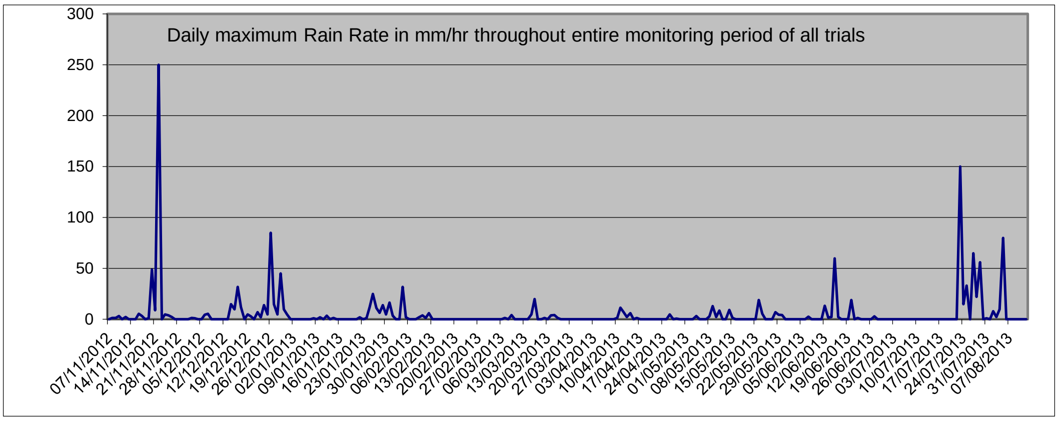


Figure 34: Measured rain rates during the trials

Results

The measuring period was from 7 November 2012 to 11 August 2013. The missing data between 22 May and 15 July 2013 was because no data was collected.

Figure 35 shows the minimum daily RSL from both out-door units (ODUs) plotted alongside the peak daily rain rate data.

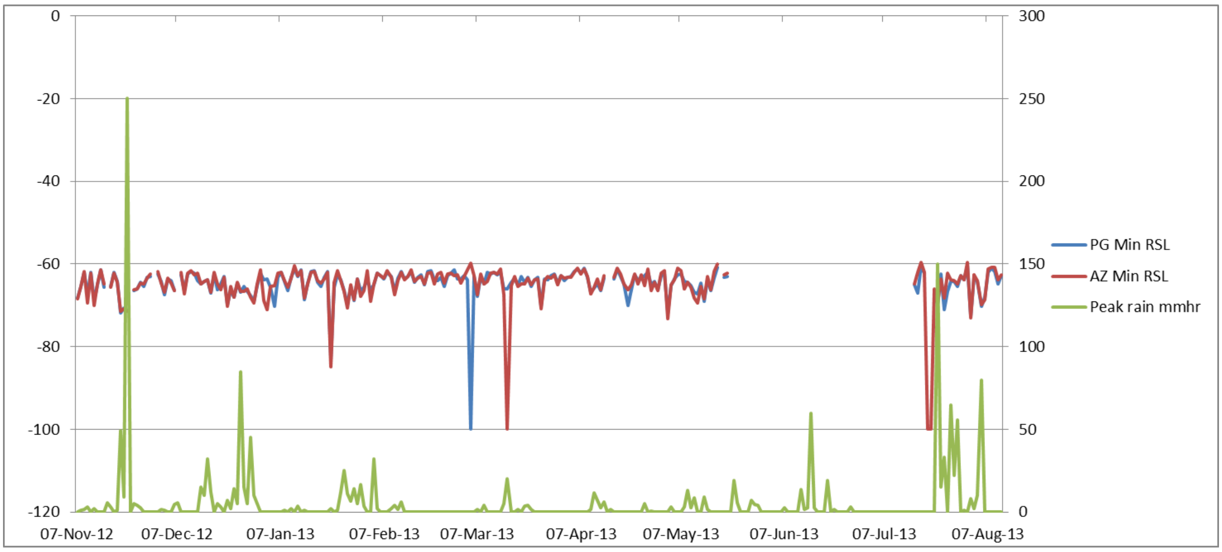
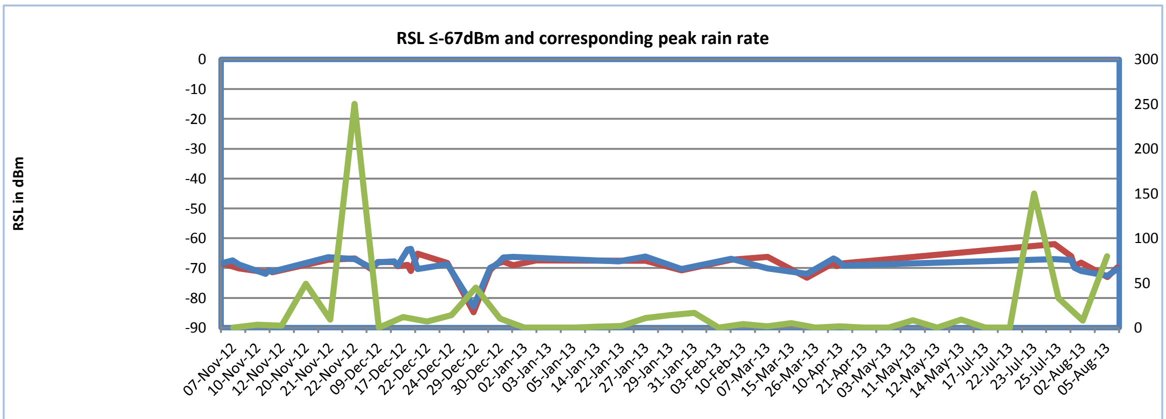


Figure 35: Maximum and minimum RSL

At this granularity there appears to be very little correlation between the significant rain events and low RSL, with many of the lowest recorded RSLs in fact appearing to occur without a corresponding rain event at all. Various filters were therefore applied to the data to try and identify patterns.

Low RSL events.



	07-Nov-12	10-Nov-12	12-Nov-12	20-Nov-12	21-Nov-12	22-Nov-12	09-Dec-12	17-Dec-12	22-Dec-12	24-Dec-12	29-Dec-12	30-Dec-12	02-Jan-13	03-Jan-13	05-Jan-13	14-Jan-13	22-Jan-13	27-Jan-13	29-Jan-13
AZ Min RSL in dBm	-69	-70	-70	-71	-71	-71	-67	-67	-70	-68	-68	-69	-69	-71	-65	-68	-85	-71	-69
PG Min RSL in dBm	-68	-67	-69	-72	-71	-71	-66	-67	-70	-68	-68	-69	-64	-64	-70	-69	-83	-70	-69
Peak rainfall mm/hr	0	3,3	2,2	49	9	250	0	12	7	14	45	10	0	0	0	1,3	2	11	14

	31-Jan-13	03-Feb-13	10-Feb-13	07-Mar-13	15-Mar-13	26-Mar-13	10-Apr-13	21-Apr-13	03-May-13	11-May-13	12-May-13	14-May-13	17-Jul-13	22-Jul-13	23-Jul-13	25-Jul-13	02-Aug-13	05-Aug-13
AZ Min RSL in dBm	-68	-69	-67	-68	-68	-71	-67	-66	-73	-68	-69	-68	-62	-66	-69	-68	-73	-70
PG Min RSL in dBm	-67	-66	-67	-68	-66	-70	-67	-70	-72	-67	-67	-69	-67	-67	-70	-71	-73	-70
Peak rainfall mm/hr	17	0	4	1,5	5	0	1,5	0	0	8,5	0	9,2	0	0	150	33	8	80

Figure 36: Zoomed in view of fading events below -67dBm

The link is fixed at 16QAM during this trial, so -67dBm was chosen as the event threshold, and every instance where either end of the link went below -67.0dBm is plotted in the graph in Figure 36.

Low RSL Observations

- In total there were 37 instances of the RSL reaching the -67dBm threshold point at one end of the link or the other, from a statistical sample of 277.

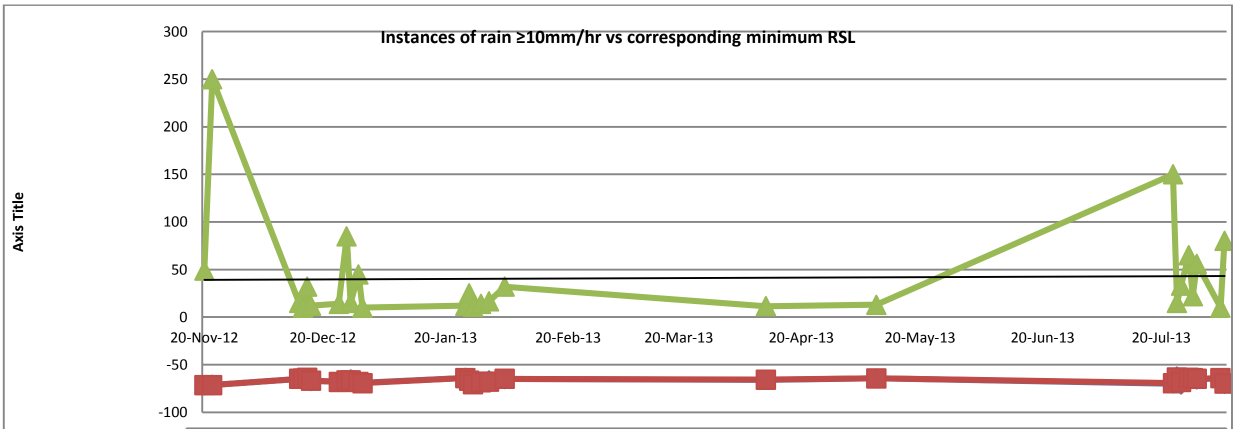
- The deepest fade occurred on 22 January, and was caused by wet snow.
- 12 of these fades (32%) occurred on days with zero rain. This is concerning, as it implies that the system is being driven into significant (>9dB) fades. The most likely explanation is that these fades are due to multipath from the flat rooftop.
- 27 of these fades (73%) occurred on days with less than 10mm/hr of rain
- Only 5 of these fades (13%) were as a result of rain rates in excess of the 0.01% figure.
- The average delta between the RSL figure at each end was only 1.4dB, indicating good RSL tracking accuracy. However 6 instances exceeded a 2.5dB delta and 3 instances exceeded a 5dB delta, with both positive and negative perturbations. It is worth noting here that the radio link uses FDD.
    - Diffraction loss as the diffractive index changes. This could easily be affecting the link, especially across the roof of the Aztec Centre
    - Multi-path/ducting. Very little is known regarding these effects in this band, as it is generally considered only for lower frequency and longer links.
    - Scintillation. A known effect at >40GHz

High Rainfall

The 0.01% rain rate for Bristol is 38.5mm/hr, but for the purposes of this investigation any rainfall events ≥10mm/hr were plotted and can be seen in Figure 37.

High Rainfall Observations:

- In total there were 27 instances of a rainfall ≥10mm/hr, from a statistical sample of 277 days measured.
- Unlike the low RSL case, there was very close tracking of the delta between the RSL at each one of the links, with a mean average of 0.45dB across all instances, and only a single instance where more than a 2.5dB delta was recorded. This implies that in the case of higher rainfall, it becomes the dominant effect, perhaps negating any multi-path effects.
- The amount of fade caused by the different rain events did not appear to show any correlation between rain rate and faded RSL level, which is hard to explain, and again points to another effect which is as yet not understood.



	20-Nov-12	22-Nov-12	14-Dec-12	15-Dec-12	16-Dec-12	17-Dec-12	24-Dec-12	26-Dec-12	27-Dec-12	29-Dec-12	30-Dec-12	25-Jan-13	26-Jan-13	27-Jan-13	29-Jan-13	31-Jan-13	04-Feb-13	11-Apr-13	09-May-13	23-Jul-13	24-Jul-13	25-Jul-13	27-Jul-13	28-Jul-13	29-Jul-13	04-Aug-13	05-Aug-13
PG Min RSL	-71,9	-71,2	-64,9	-64,3	-63,8	-67	-68,1	-66,8	-65,5	-67,7	-69,1	-63,8	-66,5	-69,9	-68,8	-66,5	-65,1	-65,8	-64,4	-69,9	-62,5	-71	-64,3	-64,3	-65,4	-64,3	-70,3
AZ Min RSL	-71,4	-71,4	-64,8	-64,3	-63,8	-66,8	-68	-66,6	-66,6	-68	-69,4	-64,1	-66,7	-70,6	-68,6	-67,9	-64,8	-65,7	-64,4	-69,4	-63,6	-68,2	-63,9	-64,1	-64,8	-64,1	-69,8
Peak rain mmhr	49	250	15	10	32	12	14	85	15	45	10	12	25	11	14	16,5	32	11,5	13	150	15	33	65	22	56	10	80

Figure 37: Instances of rain ≥10 mm/hr vs corresponding minimum RSL

RSL during Rain Free periods

As a result of the seeming lack of correlation between rain events and RSL, it was decided to plot the min/max RSL for all "no rain" days, which resulted in the graph in Figure 38.

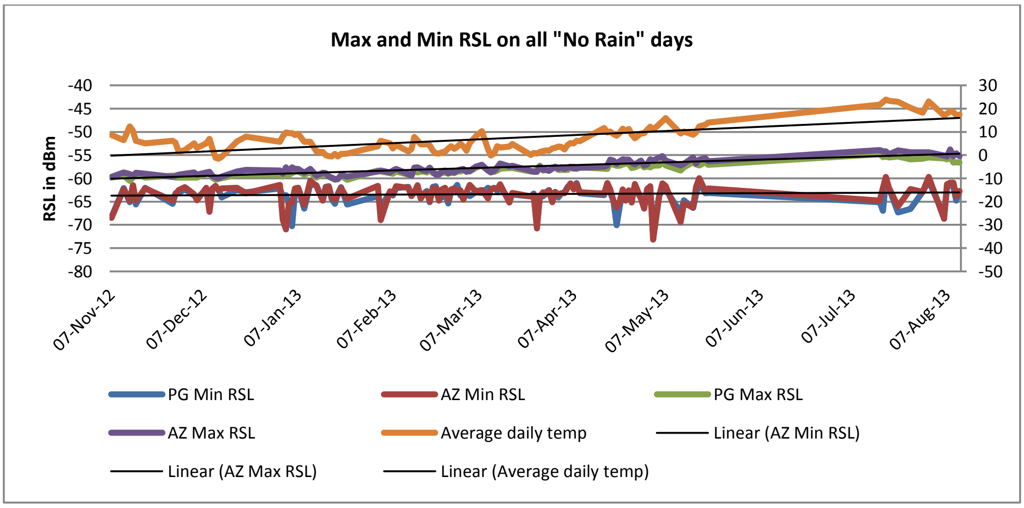


Figure 38: Maximum and minimum RSL on all no rain days.

Even on "no rain" days, there is a considerable daily variation between maximum and minimum RSL. If the trend lines are plotted, then there is circa 2.5dB of average daily variation at the beginning of the test period, but nearly 8dB variation by the end.

It is noted that the absolute level of the maximum RSL is around -55dBm by the end of the test period which is circa 3.5dB above the calculated figure.

The trend line for minimum RSL shows no significant alteration across the measurement period, varying less than 0.5dB.

Conclusions

Whilst there appears to be some definite and fully expected correlation between rain intensity and fade depth, a lot of the data recorded appears counter intuitive, and indicates either a significant multi-path effect, probably from the roof of the Aztec centre, or an equipment issue.

Most 60GHz radios deployed to date (worldwide) appear to have been at rooftop level, for LAN extension etc., and as such no vendor approached to date appears to have good modelling data for street level deployment, or have considered multi-path/ducting or even in most cases scintillation within its link calculation tools. It will be interesting to see other street level deployments if they would yield similar results, as this could be directly relevant to the usefulness of 60GHz in such deployment scenarios.

Street-level trials

This trial is reported by Siklu.

Scope

In this trial V-band mm-wave radio links were used to backhaul one of the world's largest sports events in an outdoor environment. The mm-wave radio served as backhaul for Wi-Fi access points providing free Wi-Fi service for 45,000 spectators participating in the event. The objective was to assess the effects of city infrastructure, canyon style streets, traffic and weather patterns and the effect any of these may have on wireless links in an urban environment.

The operator required a wireless-based fibre extension solution with:

- Ease of installation
- High capacity
- Street level deployment
- Interference free band
- Zero footprint (backhaul unit should not be wider than the pole it is installed on)
- 99.95% availability target for the highest capacity (1000Mbps).

Setup

The V-band radio performance has been monitored and correlated with weather statistics. The radio was set to provide 1000Mbps performance using 500MHz channel bandwidth (TDD). The deployments are depicted in Figure 39 and Figure 40.

Figure 39: Testing phase installation

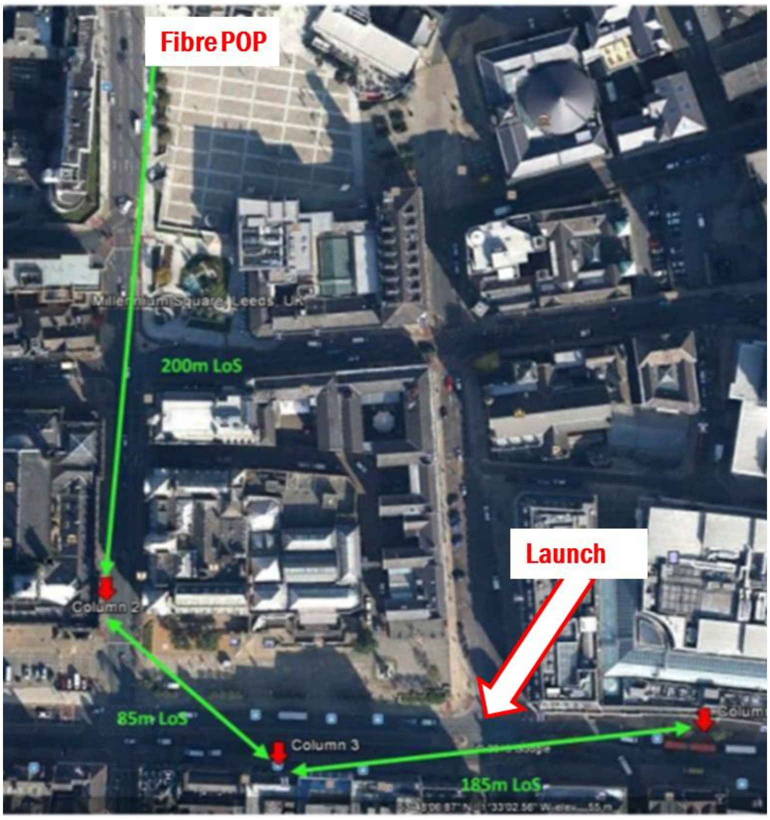


Figure 40: 60 GHz link locations

The following parameters were monitored during the trial:

- Rainfall
- Temperature
- Humidity
- Wind
- Pressure
- Received signal level (every 1s)
- Any change in throughput (modulation/BW – event driven)
- BER

Results

The availability was as expected according to link budget calculations taking into account the oxygen absorption and rain statistics.

Figure 41 shows the RSL and rain rate measurements. Rain had very little impact on the performance and that can be explained by physics. In rain zone F, for example at 99.999% availability which is much more that is expected from the small cell backhaul, for a 200 meter link the rain causes 4 dB of attenuation, and at 99.99% it is around 2 dB. That is well within the design spares that are taken into account.

Expected attenuation (rain zone F):

~ 4dB @ 99.999% for 200m link

~ 2dB @ 99.999% for 85m link

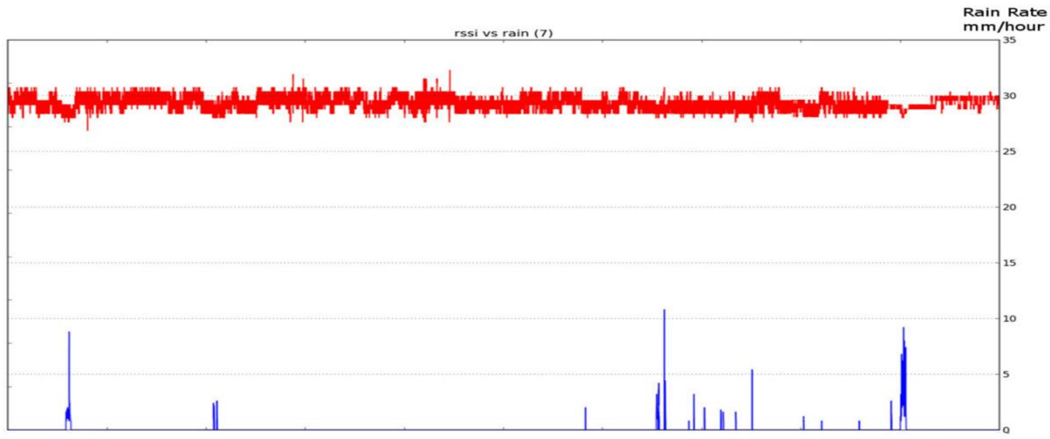


Figure 41: Correlated Rain [blue] / RSSI [red] of operational V-band radio

Figure 42 shows RSL and wind measurements. Wind had no impact on the performance.

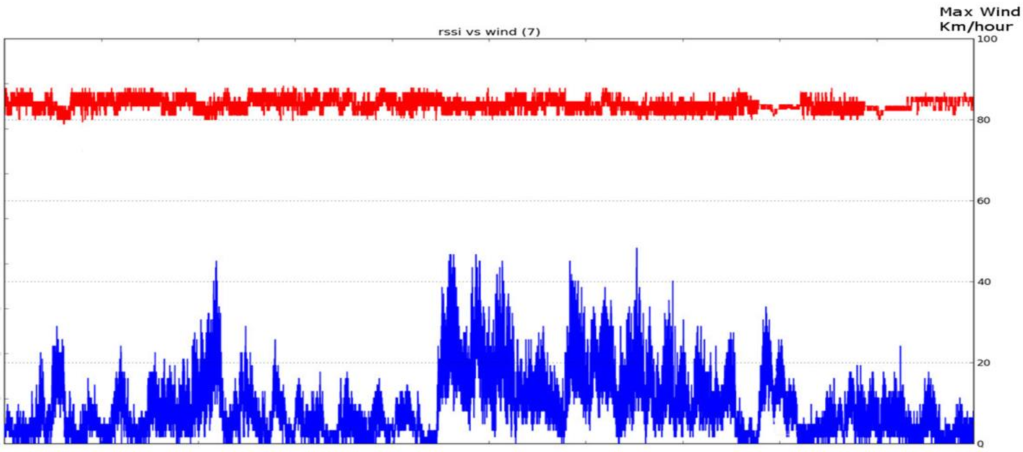


Figure 42: Correlated Wind [blue] / RSSI [red] of operational V-band radio

Conclusions

The mobile operator was satisfied after the 3 months of field testing and concluded:

”We have been impressed with how well the 60 GHz radios have performed. During the trial, they were tested with both rain and varying wind conditions, which often disturbs the unit's position on the pole, and have continued to run smoothly”

Gigabit to the home service in San Francisco, California, USA

This trial is reported by Siklu.

Scope

The scope of this trial was to provide wireless gigabit services to residential customers in the San-Francisco area. V-band radios were used to create a meshed, rooftop-based, network. The winter storm “Stormageddon” hit San Francisco during the winter of 2014. While the rainfall rate reached 4.28 inches within 48 hours and strong winds caused power shut-downs in many parts of the city, the network’s longest length V-band radio (730 meters) performed impeccably.

The operator required:

- Ease of installation
- High capacity
- Small footprint (most links deployed on rooftops)
- Interference free band
- 99.9% availability target for the highest capacity (1000Mbps)
- Extended MTBF for minimizing future site visits (‘deploy and forget’ approach)

Setup

The link deployment is depicted in Figure 43.

Figure 43: V-band link serving residential customers, San Francisco 2014.

Operational service testing performed by the operator:

- Sub-1mSec delay
- Gigabit capacity
- Reliable SNMP based sampling of radio and capacity parameters
- Continuous operation through winter storms.

Results

Capacity dropped due to weather conditions, but services were continuous thanks to hitless adaptive bandwidth and coding modulation. See Figure 44 with RSSI and SNR parameters measured throughout the storm.

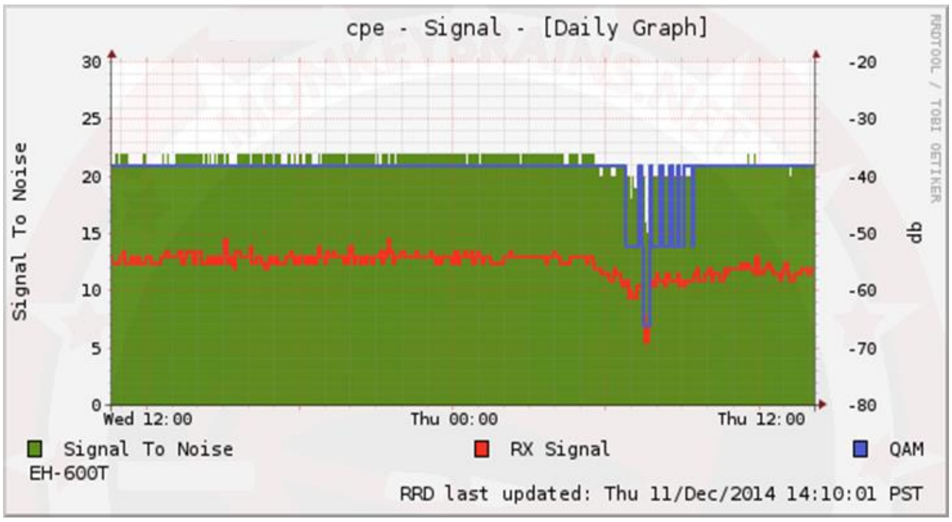


Figure 44: V-band link performance during San-Francisco 2014 winter storm

Conclusions

Actual performance exceeded the design goals, keeping 100% daily availability for the 730m link, even at the storm's heaviest rains periods. The operator concluded: "Gigabit to the home is doing just fine during 'Stormageddon'".

Street-level V-band radio link assessments for LOS and bounced-path-NLOS conditions in dense urban environment

This trial is reported by DragonWave Inc.

Scope

A series of street level tests were conducted across numerous test sessions in order to characterize radio link delay spreads and radio system performance in various LOS and bounced-path-NLOS path conditions. The goals of this characterization testing were:

- Confirm specific antenna & radio-product designs that were targeted at street level backhaul deployments at 28, 38 & 60 GHz, where street light poles and traffic light poles were the primary mount structures (only 60 GHz data is reported here)
- Confirm antenna mounting height recommendations needed to optimize operation in the presence of various "downtown" vehicular traffic conditions
- Create a knowledge-base from which street-level backhaul networks can be designed/implemented to achieve useful availability

It should be noted that the information reported here is the result of most recent test sessions at V-band. These sessions were preceded by "engineering" sessions whose goals were more related to gathering engineering field data related to RF channel characteristics needed to undertake radio designs targeted at addressing the propagation characteristics of street-level backhaul links.

Through previous test sessions, different radio link configurations were tested (simultaneously with both channel sounders and with DragonWave Avenue Link backhaul radio systems). These previous undertakings were used as design inputs used to complete the DragonWave Avenue Link product design. The information reported here is derived from a series of confirming field-test sessions undertaken in late 2013 and early 2014.

Setup

The general test conditions used for this testing were as follows:

LOS Confirmation – Test scenario

- 5m AGL install height ("street level" installations)
- 58 GHz operation
- Link paths designed/configured to run diagonally across the open area of the street, from intersection to intersection. A design attempt was made to avoid blockage (i.e. foliage) conditions as being non-viable, however, some foliage blocked paths were included for confirmation of this assertion
- Variety of paths selected for different ranges (150m to 450m), various building/foliage clutter combinations along the street sides
- Focus on heavy vehicular traffic conditions (rush hour) where widespread, selective fading is most likely (effectively results in quasi-flat fading of the band)
- Measurements: Delay spread performance of the path, RSL levels (predicted vs achieved), modulation-depth confirmation

The LOS paths used in this series of tests are shown in Figure 45.

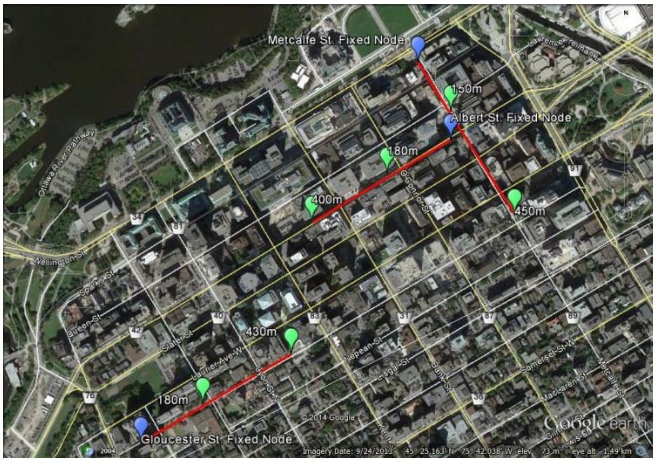


Figure 45: Overview of Employed LOS Paths

NLOS (Bounced-Path) Confirmation – test scenario

- 5m AGL install height ("street level" installations)
- 58 GHz operation
- Link paths established using predicted (pre-designed) reflecting surfaces
- Variety of paths selected for different ranges (150m to 450m), various building/foliage clutter

- Focus on heavy vehicular traffic conditions (rush hour) where widespread selective fading is most likely (effectively results in quasi-flat fading of the band)
- Measurements: Delay spread performance of the path, RSL levels (predicted vs achieved), modulation-depth confirmation

The bounced-path NLOS paths used in this test series is shown in Figure 46.

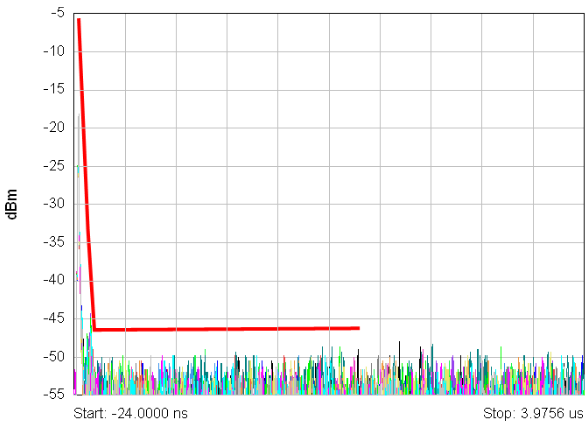
Figure 46: Overview of Employed Bounced-Path NLOS Paths

Results

LOS Street Level Links

A partial summary of link results is shown in Figure 47. There is in general good correlation between predicted and measured link performance. Also shown is the channel impulse response showing the envelope of the delay spreads recorded as well as a typical sounding. This information enables confirmation of installation practices, antenna/radio designs and path design in these dense urban scenarios where without these design measures, multi-path and vehicular traffic can have severe impacts on radio link performance.

Test Path #	Separation, m(as the crow flys)	Description of Path	PTx (dBm)	Predicted RSL (dBm)	Measured RSL (dBm)	Approx Prediction Error (dB)	Achieved error-free modulation	Notes
1	180	Dense downtown, 4 lane roadway, no foliage	4	-48	-48	0	256QAM & 512QAM	heavy traffic
2	180	Dense downtown, 4 lane roadway, no foliage	4	-48	-47	-1	256QAM & 512QAM	no/light traffic
3	400	Dense downtown, 4 lane roadway, no foliage	4	-58	-56	-2	QPSK	heavy traffic, minor errors
4	400	Dense downtown, 4 lane roadway, no foliage	4	-58	-57	-1	QPSK	no/light traffic, minor errors
5	150	Dense downtown, 4 lane roadway, no foliage	4	-46	-51	5	256QAM & 512QAM	heavy traffic
6	450	Dense downtown, 4 lane roadway, slight road-rise at one end of the path, no foliage	4	-60	-57	-3	256QAM & 512QAM	heavy traffic
7	180	Dense downtown, 4 lane roadway, foliage along one side	4	-48	-48	0	256QAM & 512QAM	heavy traffic
8	430	Dense downtown, 4 lane roadway, foliage along one side causing some blockage	4	-59	no link		N/A	heavy traffic, foliage blocked link



Envelope trace (red) = recorded delay spread envelope for all soundings

Lower traces = V and H polarized soundings for a single path from the dataset

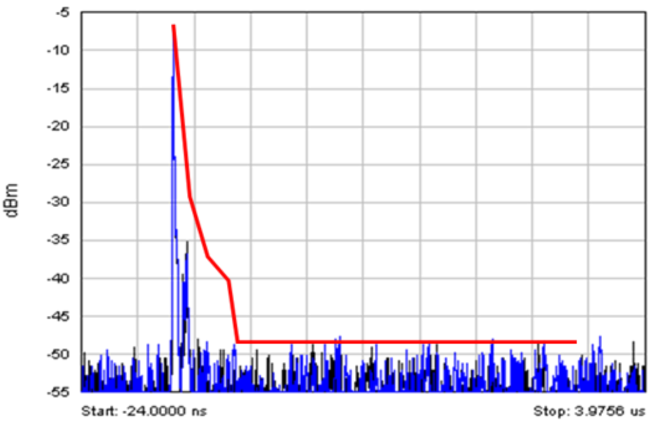
Figure 47: Measured Results for LOS Path Conditions

Bounced Path NLOS Street Level Links

A partial summary of link results is shown in Figure 48. In this case, a fixed reflection loss is assigned to the predicted path loss. This is a result of other work undertaken in this area. The use of a single fixed value is based upon the desire to avoid detailed characterization of each bounce surface which may be employed in a large-scale deployment (which isn't scalable). As expected the errors between measured and predicted performance are larger than in the LOS case. The large reflection losses will allow this deployment technique to be used on shorter path hop lengths. Because of the lower degree of performance predictability, this deployment technique would be less attractive in network design and therefore used sparingly. However, it does represent a viable way to improve the overall coverage performance of a given street level backhaul networking solution.

Also shown is the channel impulse response showing the envelope of the delay spreads recorded as well as a typical sounding. This information enables confirmation of installation practices, antenna/radio designs and path design in these dense-urban scenarios where without these design measures, multi-path and vehicular traffic can have severe impacts on radio link performance.

Test Path #	Separation, m(as the crow flys)	Beam path length, m	Approx angle of incidence to reflection point	Reflecting Surface Description	PTx (dBm)	Predicted reflection loss (dB)	Predicted RSL (dBm)	Achieved RSL (dBm)	Approx Prediction error (dB)	Notes
2	70	100	80	glass & metal, 95% tinted glass cover, smooth surface with minor irregularities	4	35	-77	-77	0	low/limited vehicular traffic
3	70	150	60	glass & brick, 50% tinted glass cover, medium surface irregularities	4	35	-81	-73	-8	low/limited vehicular traffic
5	70	100	80	glass & metal, 95% tinted glass cover, smooth surface with minor irregularities	4	35	-77	-79	2	heavy traffic, with percipitation
6	70	150	60	glass & brick, 50% tinted glass cover, medium surface irregularities	4	35	-81	-75	-6	heavy traffic, with percipitation
8	60	90	75	glass & concrete, 30% tinted glass cover, minor smoothness irregularities	4	35	-76	-69	-7	low/limited vehicular traffic
9	60	90	60	glass & concrete, 30% tinted glass cover, minor smoothness irregularities	4	35	-76	-51	-25	low/limited vehicular traffic
10	60	90	60	glass & concrete, 30% tinted glass cover, minor smoothness irregularities	4	35	-76	-41	-35	heavy traffic
11	60	90	70	glass & concrete, 30% tinted glass cover, minor smoothness irregularities	4	35	-76	-48	-28	heavy traffic
12	110	125	75 - 80	glass & concrete, 30% tinted glass cover, minor smoothness irregularities	4	35	-80	-78	-2	heavy traffic, unstable link reflection geometry not ideal



Envelope trace (red) = recorded delay spread envelope for all soundings

Lower traces = V and H polarized soundings for a single path from the dataset

Figure 48: Measured Results for Bounced-Path NLOS Path Conditions

Conclusions

We have shown channel measurements from street-level deployments of V-band radios. The measured LOS links in general show good correlation between predicted and measured performance. However, it is difficult to predict the reflected NLOS channel performance. The large reflection losses will allow this deployment technique to be used on shorter hop lengths. Because of the lower degree of performance predictability, this deployment technique would be less attractive in network design and therefore used sparingly.

Mast sway field test

This trial is reported by Nokia.

Scope

To provide some real-life background for backhaul mm-wave beam steering algorithm development, mast movement field measurement data is presented here. Over 19 000 hours of typical small-cell installation site (Figure 49) movement measurements were done during 2014.

Setup

A dedicated deflection measurement unit was constructed that recorded movement of structures in three dimensions. These movements (accelerations) were converted to movement around mast longitudinal axis (twist and sway) of this axis, Figure 50. Grey patterns show how antenna beam alignment would change if there is a radio attached to the structure.

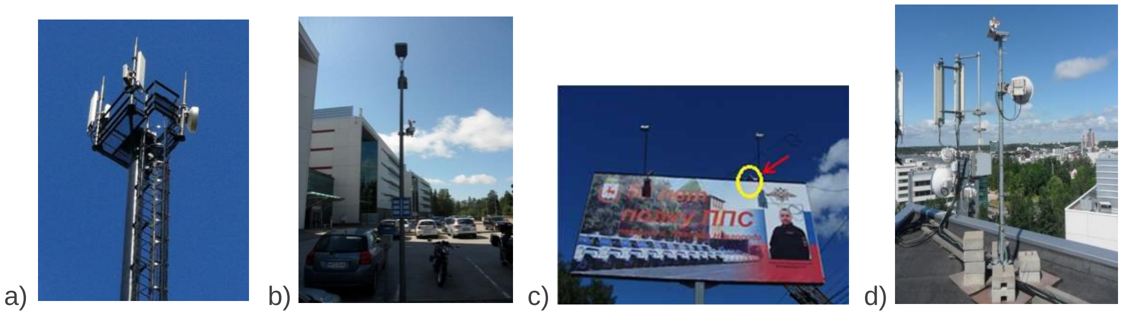


Figure 49: Typical small-cell sites a) telecommunication mast, b) lamp pole, c) billboard and d) rooftop BTS site.

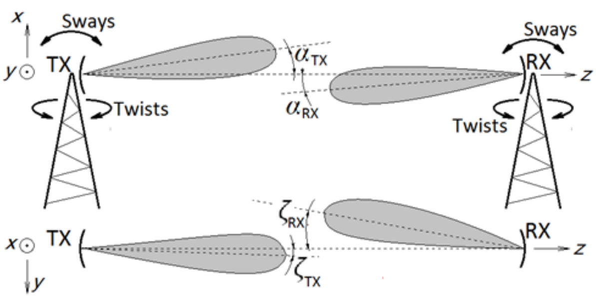


Figure 50: Illustration of twist and sway movements in vertical structure seen from side (upper picture) and from top (lower picture).

Type of mounting structures	Number of locations	Number of measurement runs	Overall duration, hrs.
Russia			
Metal and metal-concrete high telecommunication masts	6	17	3700
Thick lamp pole	1	5	1400
Thin lamp posts	2	8	1750
Traffic lights post	2	11	2400
Billboards	2	11	2450
Finland			
Parking lot Poles	4	16	2900
Private building rooftop pole	1	3	2800
Office building rooftop pole	1	3	2300
Total	**6**	**22**	**19700 hours**

Table 11: Measurement sites

Results

The practical implications of sway may be quantified by assuming a narrow-beam radio link in swaying masts and calculating the statistical effect of misalignment. In addition to dynamic deflections, static initial misalignment contributes to radio link unavailability. Here we assume that the initial misalignment angle is uniformly distributed over half-power beamwidth of the antenna used. A summary of all measured mounting structures' total misalignment joint distribution combining twist and sway together with initial misalignment, and assuming 1° HPBW antenna, are presented in Figure 51. All structures encounter small movements and at very low probability levels the differences are clearly visible. The use of very high gain antennas can cause severe outage probability if installed on certain structures like billboards and lamp poles, while other structures provide acceptable quality even with very narrow beamwidths. For example at 60 GHz, assuming antenna efficiency 0.65, beamwidth of 1 deg. corresponds to 34 cm diameter parabolic antenna with 45 dBi gain.

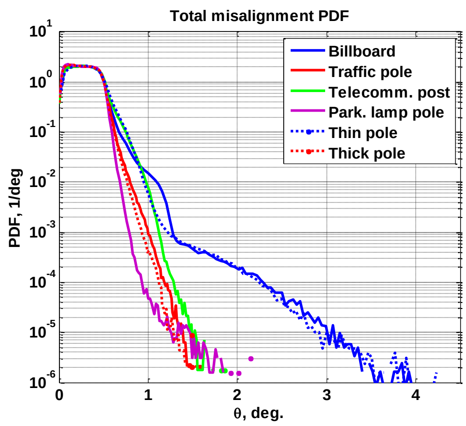


Figure 51: PDFs of total antenna misalignment for HPBW 1°.

Moreover, since several measurement devices were equipped with a wind speed sensor, correlation between deviations and wind speed was also confirmed and analysed. The typical measured sites are shown in Figure 49.

Figure 52 shows the deflection statistics for a high telecommunications pole in Figure 49a. Maximum PDF deflection range at 10^{-6} level is 1.2 degrees in twist and 2.9 degrees in sway.

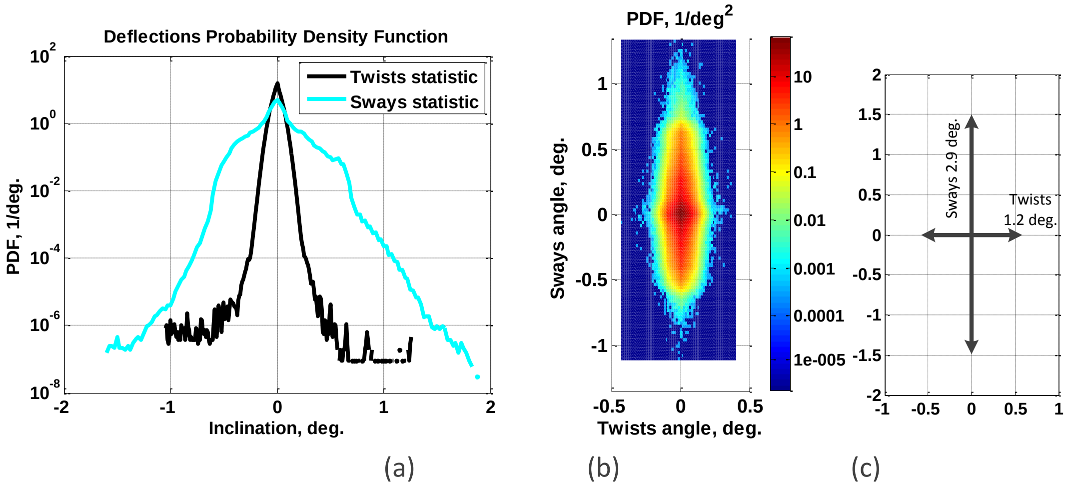


Figure 52: Telecommunication pole deflection statistics: a) twists and sways PDFs, b) 2D deflections PDF, c) deflection range

Figure 53 presents the twist and sway PDFs for billboard and short lamp pole. Maximum twist range in a) is 1.5 degrees and sway is 7 degrees, and in b) 1.2 and 3 degrees, respectively.

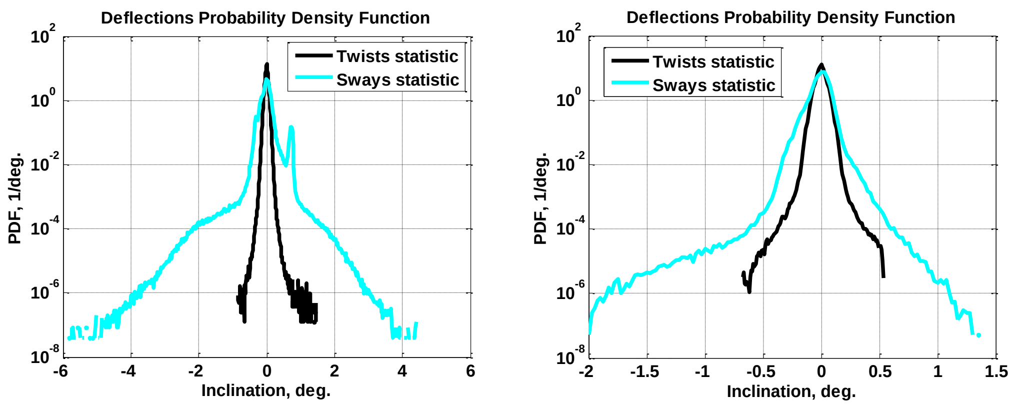


Figure 53: PDF statistics for a) billboard and b) short lamp pole installations.

Based on the analysed measurement results, mast structures encounter fast and slow movements. It was also found that some vibrations are periodic while others are not. It is clear that wind has an effect on all structures and resulting fast vibration is very much dependent on mechanical construction and wind speed. Direct sun heating caused noticeable slow movement (bending) in most masts. Also some random vibrations were detected that may be a consequence of surrounding interference.

Effects of mast deflections on link budget

Path loss of a line-of-sight mm-wave hop can be expressed with an extended Friis equation with deterministic and statistical components:

$$10\lg\left(\frac{P_r}{P_t}\right) = 20\lg\left(\frac{\lambda}{4\pi R}\right) + G_1(\alpha_1,\zeta_1) + G_2(\alpha_2,\zeta_2) - \gamma_{O_2}\cdot R - \gamma_{rain}\cdot R,$$

Free space path loss and atmospheric gas absorption remain constant for a particular distance. However, attenuation due to rain (snow and mist), misalignment and antenna gain variation due to twist and sway cause statistical variations that contribute to error statistics or unavailability, depending on the link dimensioning.

Figure 54 illustrates statistical degradations for link budget due to mast deflections.

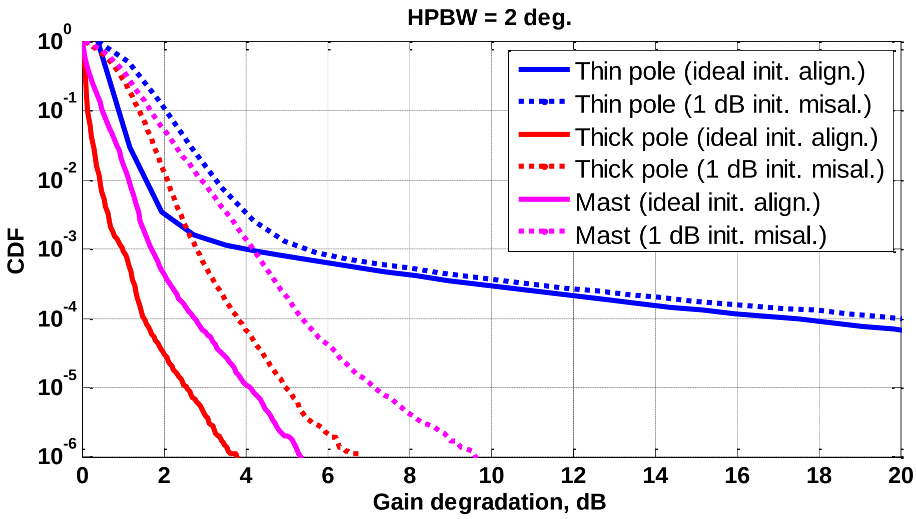


Figure 54: CDF attenuation due to deflections (three types of sites, HPBW = 2 deg.).

Compared to rain attenuation or outage probability, attenuation caused by deflection does not depend on hop length. It depends only on mounting structure and antenna characteristics.

For a set of link parameters a joint rain and deflection CDF of these two uncorrelated attenuation factors can be evaluated. If targeted availability level is low (couple of ‘nines’) the rain induced loss is dominant. On the contrary, for example in Figure 55 for thin poles the deflection dominates at short distances and degradation reaches 20-30 dB for the distances of several hundred meters.

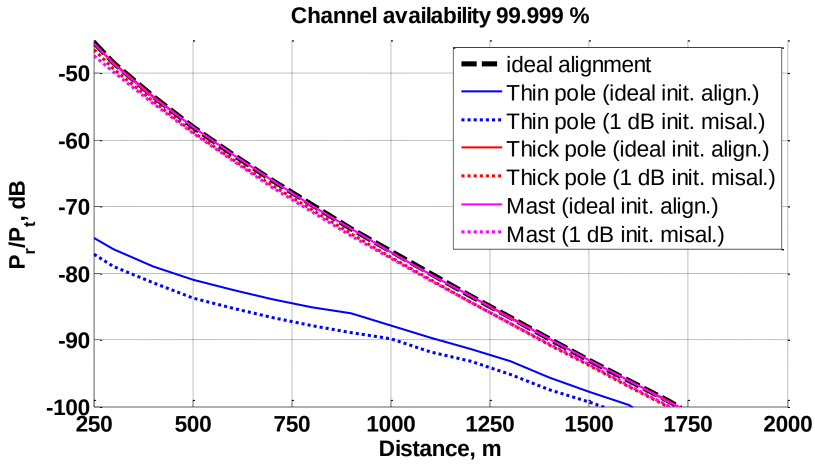


Figure 55: Link budget vs. Distance for availability level 99.999% (frequency 75 GHz, HPBW = 2 deg.).

Conclusions

Mast movement field measurement data have been reported to provide some real-life background for millimetre wave backhaul reliability. Over 19 000 hours of typical installation site movement measurements were collected and analysed. All installation structures encounter small movements and at very low probability levels the differences become clearly visible between the different installation structures.

Final Conclusions

The main contribution of this white paper is the reported experience from fourteen different field trials with E-band and V-band radios. The reported trials have been independently made by the contributing companies and have therefore different ambitions and scopes. For example, trials range from long-term E-band trials in traditional LOS deployments with years of collected data to shorter proof-of-concept trials using V-band in more non-traditional nLOS and NLOS deployments. However, the E-band trials consistently show that E-band technology provides carrier-grade Gigabit-per-second performance in traditional LOS installations and that the performance can very well be predicted by using standard ITU-R prediction models. Also V-band radio performance is excellent when deployed properly and it can also be predicted using existing models in LOS conditions. But as the V-band radios are moved into nLOS or NLOS in street-level deployments, multi-path propagation makes it very difficult to predict the radio performance which makes planning more difficult.

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Abbreviations

For the purposes of the present document, the following terms and abbreviations apply:

ACM	Adaptive Coding and Modulation
AGL	Above Ground Level
AM	Adaptive Modulation
BER	Bit Error Rate
ES	Error Second
ETSI	European Telecommunications Standards Institute
FDD	Frequency Division Duplexing
HPBW	Half-power Beam Width
ISG	Industry Specification Group
ITU	International Telecommunication Union
LOS	Line-of-Sight
MTBF	Mean Time Between Failures
MSE	Mean Squared Error
MW	Micro Wave
mWT	millimetre Wave Transmission
nLOS	near Line-of-Sight
NLOS	Non-Line-of-Sight
NMS	Network Management System
ODU	Outdoor Unit
PLR	Packet Loss Rate
PtP	Point-to-Point
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RSL	Received Signal Level
RSSI	Received Signal Strength Indication

Rx	Receiver
UAS	Unavailable Seconds

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