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| **The 29th Meeting of the APT Wireless Group**  **(AWG-29)** |  |
| 21 – 29 March 2022, Virtual/Online Meeting | 29 March 2022 |

Source: AWG-29/OUT-25

**DRAFT APT RECOMMENDATION ON MODEL(s) FOR FWS LINK performance degradation due to wind**

The Asia-Pacific Telecommunity (APT),

*considering*

a) that many Asia-pacific region countries are often under severe weather conditions including tropical cyclones, hurricanes, and typhoons which the maximum wind speeds are very large;

b) that when antennas and their supporting structures are exposed to strong winds, the mechanical stress can generate vibrations and mechanical distortions which, in some cases, give raise to temporary deviations of the main beams from their desired directions;

c) that the above antenna fluctuation causes the degradation of link performance;

d) that the definition of methods to compensate link degradations are advisable to facilitate installation of communication infrastructure so that link performance objectives are met;

e) that the practical implementation of the above methods should be effective and should be kept, as much as possible, easy to be realized on real installations;

*noting*

1. that APT Report No. APT/AWG/REP-81 on FWS LINK PERFORMANCE UNDER SEVERE WEATHER CONDITIONS reports the severe weather conditions in APT countries, impact of severe weather conditions on link performance of fixed wireless communication, the mitigation techniques for those impact by severe weather conditions, and the case study of one of its techniques;

b) that there is no APT Recommendation specifically addressing the link performance under wind conditions before this Recommendation.

*recognizing*

the needs of countries to complement the degraded FWS link performance due to strong winds.

*recommends* that APT Members:

1. use the appropriate attenuation model shown in Annex 1 when an antenna is vibrating due to wind for link analysis;

2. adopt the technique(s) as shown in Annex 2 to improve or compensate the degraded FWS link performance due to wind;

3. refer to Annex 3 for link budget evaluation for FWS links.

Annex 1

**Attenuation model under wind condition**

1. **Background**

When the number of small cells is increased to satisfy the traffic need per area, it is unavoidable to install radio equipment even on low and vibrating structures (utility poles, street lamps, walls of buildings, etc.), in addition to the conventional high-strength steel towers. In such cases, the equipment installation would be in bad conditions, and that leads to the concern of radio quality degradation. Especially when installing antennas with narrow beams in the millimetre-wave band on an unstable pole, it is necessary to consider the influence of wind.

1. **Measurement system**

We observed the influence of wind to the millimetre-wave devices at 85.5 GHz on a pole for 6 months. A parabolic antenna with a diameter of 350 mm, a radio equipment, a weather sensor, and an acceleration sensor were installed on a steel pole with a diameter of 89 mm and a length of 5 m. Figure 1.1 shows the measurement system.



Figure 1.1 Measurement system.

We assume the static wind load given to the pole and antenna, and the calculation model is described in Figure 1.2.



Figure 1.2 Calculation model.

Figure 1.3 shows an example of the relation between the received signal level (RSL) and wind speed. In the figure, the RSL is composed of two components: one is static and the other is dynamic , such as vibration. The inclination of the pole due to static and dynamic wind load is evaluated based on this assumption and the model of the degradation of RSL is made. In this measurement system, the inclination of one side is small with respect to the other side when estimating the degradation of RSL.

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Figure 1.3 RSL and wind speed.

1. **Static component of inclination due to wind**

The inclination angle of the pole by the static wind load given to the pole and the antenna is derived as follows.

The velocity pressure for a wind velocity is shown as follows:

(1)

: Velocity pressure [N/m2]

: Air density (=1.226[kg/m3])

: Wind speed [m/s]

The static load applied to the pole and the static load applied to the antenna are calculated by:

, (2)

: Wind load applied to the pole [N] : Wind load applied to the antenna [N]

: Drag coefficient of the pole : Drag coefficient of the antenna

: Wind receiving area of the pole [m2] : Wind receiving area of the antenna [m2]

Inclination angle is calculated by,

(3)

: Young’s modulus [Pa]

: Second moment of area [m4]

: Length of the pole [m]

From above equations, the inclination angle is proportional to square of wind speed. The parameters of the mesurement system are shown in Table 1.1. For simplicity, (3) is expressed as (4). The static wind load coefficient in the mesurement system is 4.2 × 10-4 deg/(m/s)2.

[deg] (4)

Table 1.1 Parameter of the measurement system

|  |  |
| --- | --- |
| Item | Value |
| *C1*: Drag coefficient of the pole | 0.8 |
| *A1*: Wind receiving area of the pole | 0.445 [m2] |
| *C2*: Drag coefficient of the antenna | 1.1 |
| *A2*: Wind receiving area of the antenna | 0.07 [m2] |
| *E*: Young’s modulus | 2.05 × 1011 [Pa] |
| *I*: Second moment of area | 1.01 × 10-6 [m4] |
| : Length of the pole | 5 [m] |

1. **Dynamic component of inclination due to wind**

Next, the vibration of the pole is analysed based on measurement results. The pole was vibrated by wind at a natural frequency of 2.3 Hz, and the inclination of the pole is derived from the dynamic amplitude filtered from the measurement results. The maximum values of wind speed and amplitude are calculated every ten seconds. The dynamic inclination angle of the pole is proportional to square of wind speed as in the case of static wind load. The relation between wind speed and dynamic inclination is expressed in (5). The coefficient from the measurement is 4.6 × 10-4 deg/(m/s)2.

[deg] (5)

1. **FWS link performance degradation**

Based on above calculations, the inclination of the pole due to static and dynamic wind is modelled. Radiation pattern , where is the deviation angle, is expressed in (6), where is Bessel Function of the first kind and is the half power beamwidth. Figure 1.4 shows an example of radiation pattern for a value of 0.9 deg. For simplicity, this formula can be changed to a polynomial approximation. The degradation of RSL R(v) due to wind is expressed in (7), which indicates the worst value of RSL against a certain wind speed. Regarding the inclination of the pole, a misalignment angle of should be considered when the antenna is installed.

[dB] (6)

[dB] (7)

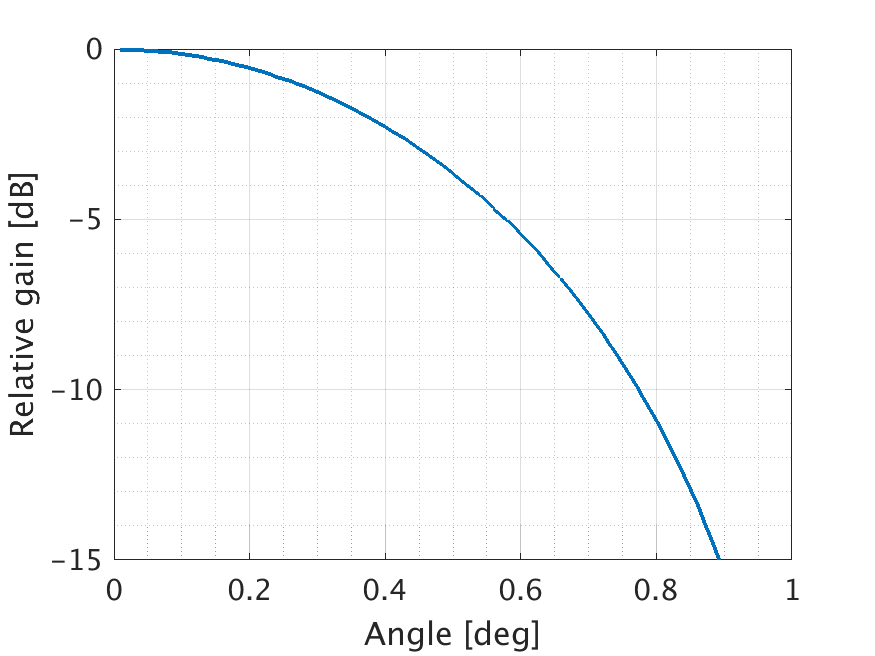


Figure 1.4 Example of radiation pattern.

Figure 1.5 shows the relation of maximum wind speed and minimum RSL for every ten seconds. The effect of each component and approximated curve of the measurement values are also shown in the figure. From the figure, the degradation of RSL due to misalignment in the measurement system is approximately 1.2 dB, which corresponds to 0.28 deg. The differences between the two curves can be attributed to the fact that the effect of the opposite site is not considered. Coefficient is similar to coefficient . Both coefficients depend on the structure of the pole; therefore, a high correlation is expected, and can be approximated to .

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Figure 1.5 Maximum wind speed versus minimum RSL.

Regarding the opposite site, the minimum RSL is also calculated. Therefore, the worst RSL of the FWS link is estimated as a sum of the minimum RSL of both sites as described in (8), where and are the minimum RSL of each site.

(8)

As shown in Figure 1.5, the measurement results of the inclination of the pole and the calculation model matched well; thus, the performance degradation of FWS links can be estimated from some parameters and coefficients of the FWS link configuration.

Furthermore, the probability of the RSL is estimated from wind speed. The cumulative distribution function (CDF) of wind speed is expressed by Weibull distribution as shown in (9). An example of the measurement is shown in Figure 1.6. Weibull coefficient, scale factor *k* equals 0.86 and shape factor *c* equals 1.03. The wind speed corresponding to a probability of 99.999% was 17.8 m/s.

(9)

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Figure 1.6 Wind speed distribution.

From (9), the wind speed is expressed by (10). Considering the initial antenna misalignment, the relation between the cumulative probability and degradation of RSL is derived from (10) and (11) as shown in (12).

[m/s] (10)

[deg] (11)

[dB] (12)

Figure 1.7 shows the CDF of the gain degradation derived from the relation between wind speed and degradation of RSL. The initial alignment error is also considered. Although there are remained differences, the model and the measurement results matched quite well.

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Figure 1.7 CDF of gain degradation (=0.28 deg.).

In conclusion, the measurement results of the inclination of the pole and the calculation model matched well; thus, the performance degradation of FWS links can be estimated from some physical parameters and coefficients of the FWS link structure.

1. **Calculation example**

As the calculation examples, six cases are considered as follows. Table 1.2 shows the parameters of the cases. The differences between the cases are the diameter and length of the pole, antenna, and initial alignment error.

Table 1.2 Parameter examples

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Item | Unit | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
| Parameter of the pole |  |  |  |  |  |  |  |
| *C1*: Drag coefficient of the pole |  | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| : Length of the pole | m | 5 | 5 | 10 | 5 | 5 | 10 |
| Diameter of the pole | mm | 89 | 89 | 165.2 | 89 | 89 | 165.2 |
| Thickness of the pole | mm | 4.2 | 4.2 | 10 | 4.2 | 4.2 | 10 |
| *A1*: Wind receiving area of the pole | m2 | 4.45 ×10-1 | 4.45 ×10-1 | 1.65 | 4.45 ×10-1 | 4.45 ×10-1 | 1.65 |
| *E*: Young’s modulus | GPa | 205 | 205 | 205 | 205 | 205 | 205 |
| *I*: Second moment of area | m4 | 1.01 ×10-6 | 1.01 × 10-6 | 1.47 × 10-5 | 1.01 × 10-6 | 1.01 × 10-6 | 1.47 × 10-5 |
| Parameter of the antenna |  |  |  |  |  |  |  |
| *C2*: Drag coefficient of the antenna |  | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Diameter of the antenna | m | 0.32 | 0.32 | 0.32 | 0.65 | 0.65 | 0.65 |
| *A2*: Wind receiving area of the antenna | m2 | 8.04 × 10-2 | 8.04 × 10-2 | 8.04 × 10-2 | 3.32 × 10-1 | 3.32 × 10-1 | 3.32 × 10-1 |
| Beamwidth of the antenna | deg | 0.9 | 0.9 | 0.9 | 0.45 | 0.45 | 0.45 |
| *Cs*: Static wind load coefficient |  | 4.40 × 10-4 | 4.40 × 10-4 | 3.07 × 10-4 | 1.03 × 10-3 | 1.03 × 10-3 | 4.68 × 10-4 |
| *Cd*: Dynamic wind load coefficient |  | 4.40 × 10-4 | 4.40 × 10-4 | 3.07 × 10-4 | 1.03 × 10-3 | 1.03 × 10-3 | 4.68 × 10-4 |
| *θ0*: Initial alignment error | deg | 0 | 0.2 | 0.2 | 0 | 0.2 | 0.2 |

The calculation results are shown as follows. Wind speed versus inclination of the pole is calculated using (11), and the results are shown in Figure 1.8.

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Figure 1.8 Inclination of pole.

Figure 1.9 shows the gain degradation. In this figure, 0 dB is the gain degradation of a 0.6 m antenna. When the wind speed increases, the gain degradation of the 0.6 m antenna becomes larger than those of a 0.3 m antenna.

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Figure 1.9 Gain degradation.

The CDF of the gain degradation is calculated using (12) and the results are shown in Figure 1.10. The probability of gain degradation is large for the 0.6 m antenna; however, it is small for the 0.3 m antenna under the strong wind condition. In these examples, a more robust pole is required for a 0.6 m antenna.

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Figure 1.10 CDF of gain degradation.

1. **Practical planning and installation rules to minimize E-Band link degradation due to wind**

From the experience of large-scale deployment of E-Band links, it is recommended that specific rules should be followed in planning and installation of FWS links to avoid performances degradation.

**7.1. E-Band antenna characteristics**

In E-Band frequency range, i.e., 71 - 76 and 81 - 86 GHz, the typical gain of the antenna tends to be very high. Consequently, the radiation pattern envelope (RPE) beamwidth becomes very narrow.

Table 1.3 shows gains and 3-dB beamwidths of typical E-Band antennas . The RPE beamwidth is less than 1.0 deg for a 30 cm antenna type, and reduces to approximately 0.5 deg for higher gain antenna types.

For comparison, a typical 60 cm antenna at 38 GHz has a 0.9 deg beamwidth and a 45 dBi gain, so the beamwidth is as narrow as a 30 cm E-Band antenna.

Table 1.3 Typical specs of parabolic antenna at midrange frequency

|  |  |  |
| --- | --- | --- |
| **Antenna diameter [cm]** | **Gain [dBi]** | **3dB beamwidth [deg]** |
| 30 | ≈ 43 | 0.9 |
| 60 | ≈ 50 | 0.5 |

The antenna RPE, which represents the maximum gain in different angles guaranteed by the manufacturer, should be below the masks limit lines stated by ETSI 302 217-4.

In the E-Band, the antenna directivity is very high, the antenna gain/RPE reduces rapidly. This may cause link budget reduction when the antennas are misaligned from the main pointing direction.

By analyzing the actual radiation patterns of antennas, it is possible to point to narrow and deep radiation pattern depressions (null) between the main lobe and the first side lobes. The attenuation value in these points varies from one antenna sample to another, depending on the production procedure, and is typically from 20 to 30 dB from the center of the main lobe (Figure 1.11).

In the E-Band, the angle where the minimum level is positioned from the center can be approximately 0.5 - 0.7 deg for a 60 cm antenna and 0.8 - 1.0 deg for a 30 cm antenna.

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Figure 1.11 E-Band antenna real radiation pattern.

ETSI 302 217-4 provides requirements for installation on trellis or towers; thus, the maximum angular deviation of the antenna main beam axis is not higher than 0.3 times the half power beam width (HPBW) under conditions shown in Table 1.4.

Table 1.4Environmental condition under which the antenna kit maximum deviation

|  |  |  |
| --- | --- | --- |
| **Antenna type** | **Wind velocity**  **[m/s] ([km/h])** | **Ice load**  **(density 7 [kN/m3])** |
| Normal duty | 30 (110) | 25 mm radial ice |
| Heavy duty | 45 (164) | 25 mm radial ice |

The antenna and corresponding mounting kit are designed to maintain a limited deviation even in harsh conditions, and for E-Band cases, the resulting figures are indicated in Table 1.5 (max. deviation is less than HPBW).

Notably, these requirements refer only to max antenna deviation with respect to the pole/tower and it does not include pole/tower twist/sway effects.

Table 1.5 Antenna kit maximum deviation allowed by ETSI

|  |  |  |  |
| --- | --- | --- | --- |
| **Antenna type** | **HPBW**  **[deg]** | **0.3 times ‑HPBW**  **[deg]** | **-3 dB angle**  **[deg]** |
| 30 cm, 80 GHz | 0.9 | 0.3 | 0.5 |
| 60 cm, 80 GHz | 0.5 | 0.15 | 0.25 |

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**7.2. Tower sway characteristics**

As defined in the previous paragraph, the maximum RSL attenuation in the link is caused when the tower sway due to wind reaches approximately 0.5 deg for a 60 cm antenna and 0.8 deg for a 30 cm antenna.

Tower and poles static calculation are performed to evaluate the resistance of the structure against the wind load on the structure and on the installed antennas and equipment.

Different types of structures provide different resistance against the wind pressure; therefore, the angle of sway, which varies from tower to tower, is also dependent on the height of the installation position of the antenna (as explained in chapter 6 of this document).

Examples of deviation calculations (for a reference wind speed of 120 km/h) for a Lattice tower structure and a Monopole structure are described in Table 1.6 and Table 1.7, respectively.

In the case of Lattice tower, the maximum antenna deviation is 0.5 deg at approximately 20 m height, while in the case of Monopole tower, the maximum deviation for the parabolic antenna is approximately 0.8 deg at 33 m height.

Table 1.6 Examples of calculations for Lattice tower



Table 1.7 Examples of calculations for Monopole structure



**7.3. Practical planning and installation rules for E-Band link**

Microwave signal attenuation due to rain is much higher in E-Band compared to conventional microwave bands.

As an example, Figure 1.12 shows the comparison between the attenuation per km for a 15 GHz and E-Band link according to ITU-R standards used for link planning.

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Figure 1.12 Rain rate versus attenuation according to Recommendation ITU-R P.838.

Consequently, E-Band links are usually designed with a very high fade margin to counteract to the attenuation induced by rain.

A typical fade margin at the highest adaptive coding and modulation (ACM) are approximately 10 to 20 dB.

Therefore, a small variation of RSL due to wind pressure of the structure does not degrade the link performance because the link can still work at the maximum modulation level (unless there is a contemporary presence of strong wind and heavy rain events).

As defined in 7.1., the maximum RSL attenuation in the link is caused when the tower sway due to wind reaches approximately 0.5 deg for a 60 cm antenna and 0.8 deg for a 30 cm antenna.

To avoid high variation of RSL and degradation of link performances, the antenna position on the tower should be carefully placed, keeping it at the lowest position that can guarantee a line-of-sight clearance.

For the Lattice tower example in Table 1.6, any position can guarantee that a 60 cm antenna is swayed by less than 0.5 deg even in the case of very strong wind.

In contrast, on a flexible structure like Monopoles (see Table 1.7), it is risky to place a 60 cm antenna above 15 - 20 m because there is a high probability of having consistent RSL attenuation in case of strong wind.

Annex 2

**Technique(s) to compensate performance degradation of FWS link due to wind**

Severe weather conditions include tropical cyclones, hurricanes, and typhoons in which the maximum wind speeds are very large. Therefore, the FWS link performance is degraded due to the reduction in the received power or increase in bit error rate. To deal with this issue, the following techniques can be used:

**1. Automatic transmit power control**

Traditionally, automatic transmit power control (ATPC) techniques have been utilized in microwave radio links to combat rain fading (attenuation). This is also referred to as power diversity. Initially, the link is designed such that the transmit power is sufficiently large to achieve a given quality of service goal, such as bit error rate, under clear sky conditions. When the link experiences an attenuation due to rain, the transmit power is increased gradually up to the maximum transmission power limit set by a government authority. The specific technique used to increase or decrease the power at the transmitter, and the method to estimate the power at the receiver, can be used to differentiate ATPC techniques or algorithms.

ATPC is a feature of a digital microwave radio link that adjusts transmitter output power based on varying signal level at the receiver. ATPC allows the transmitter to operate below the maximum power for most of the time. When fading conditions occur, the transmit power will be increased as needed until the maximum value is reached. A system using an ATPC technique has several advantages compared to a system using a fixed transmit power, including consuming less transmitter power, longer amplifier life, and causing less interference to other microwave systems.

If the maximum transmit power in an ATPC system is only needed for a short period of time, a transmit power of less than the maximum value can be used to calculate interference to other systems (if certain requirements are met). On the other hand, because the maximum power is available when a deep fade occurs, the calculations of interference to the ATPC system can assume the "maximum power" carrier level.

**2. Adaptive coding and modulation**

Link adaptation, or adaptive coding and modulation (ACM), is a term used in [wireless communications](http://en.wikipedia.org/wiki/Wireless#Wireless_data_communications) to denote the matching of modulation, coding, and other signal and protocol parameters to the conditions on the radio link (e.g. pathloss, interference by signals from other transmitters, sensitivity of the receiver, available transmitter power margin, etc.). For example, EDGE uses a rate adaptation algorithm that adapts the modulation and coding scheme, and thus the bit rate and robustness of data transmission, according to quality of the radio channel. The process of link adaptation is dynamic, and the signal and protocol parameters change depending on the conditions of radio links.

The goal of [adaptive modulation](http://en.wikipedia.org/wiki/Link_adaptation) is to improve the operation efficiency of microwave links by increasing the network capacity compared to existing infrastructure and reducing the impact of interferences from environment.

Adaptive modulation is to vary the modulation dynamically in an manner without causing an error to maximize the throughput under momentary propagation conditions. In other words, a system can operate at its maximum throughput under clear sky conditions and decrease the throughput gradually under rain or wind effects.  Before development of ACM, microwave designers had to design for “the worst case” conditions to avoid link outage.

In this case, when the FWS link performance is degraded due to wind, this link can change from 1024 QAM or 256 QAM to QPSK to keep “link alive” without losing connection.

In adaptive modulation, there are many parameters that can be adjusted with respect to the channel fading, such as data rate, transmit power, instantaneous BER, symbol rate, and channel code rate or scheme. Therefore, it is important to determine which parameters to be adapted to achieve the best performance.

Notably, in practical systems, ACM is activated after ATPC. If heavy wind starts to cause attenuation increases, and fade margin drops accordingly, ATPC will be activated to compensate the drop of fade margin and keep the link performance and availability. In the case that fade margin drops outside the range of ATPC compensation, and the link performance and availability decrease accordingly, then ACM will be activated to compensate the degradation of link performance and availability. Therefore, a combination of these two techniques can be used to deal with the performance degradation of FWS link due to wind.

**3. Intelligent beam tracking antenna**

**3.1 Introduction**

Antenna de-focusing caused by structure deflection due to wind pressure was mentioned in previous chapters of this document.

In case of installation of E-Band FWS on Monopole type of structure, another effect can force the pole to sway, causing degradation of the RSL of the link.

When the sun hits one side of the Monopole, a temperature difference is established between the sunny and the shadowy side of the pole. In this case, the linear thermal expansion on the two sides is not the same, forcing the pole to bend.

An intelligent beam tracking antenna can compensate for the performance degradation of the FWS link due to wind or exposure to sunlight by keeping the antenna central beam steady in the right direction without degradation of the system performance.

The working principle of an intelligent beam tracing antenna is shown in Fig 2.1.

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Fig 2.1 Working principles of an intelligent beam tracing antenna.

When a tower/pole on which a passive antenna is installed shakes due to wind or exposure to sunlight, the beam of the passive antenna deviates from its original transmitting direction, causing RSL deterioration at the receiver end.

An intelligent beam tracing antenna can detect the direction parameters of antenna shaking. The direction parameters include the direction and angle that the antenna is shaking.

When the structure is swaying, the intelligent beam tracing antenna can adjust its reflector or sub-reflector according to the direction and angle that the antenna is shaking, and the feed source is kept still. Therefore, the beam of the intelligent beam tracing antenna deflects to the direction opposite to the shaking.

In this way, the intelligent beam tracking antenna can minimize the degradation of FWS link performance.

**3.2 Field trial**

An intelligent beam tracking antenna with an adjustable range of was produced. To verify its compensation effectiveness, a field trial was done in Russia.

The link information is indicated in Fig 2.2 and the sites information is in Table 2.1. The antenna installation is shown in Fig 2.3.

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Fig 2.2 Link information.

Table 2.1 Sites information

|  |  |  |
| --- | --- | --- |
|  | Site 1 | Site 2 |
| Site type | Monopole | self-Supporting Tower |
| Link distance | 4.3 km | |
| Link configuration | 1+0 E-band | |
| Antenna size | 0.6 m | |
| Antenna height | 36 m | 27 m |

信号と街路灯

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Fig 2.3 Antenna installation.

A field trial was done in Dec 2020 and Jan 2021. The link with the enabled intelligent beam tracking ability was tested in Dec 2020, and with disabled intelligent beam tracking ability was tested in Jan 2021. The RSL was detected and recorded separately as shown in Fig 2.4 and Fig 2.5, respectively. (Red line represents the maximum RSL level and the blue line represents the minimum level recorded in every 15 minutes).

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Fig 2.4 RSL test in Dec 2020 with enabled intelligent beam tracking ability.

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Fig 2.5 RSL test in Jan 2021 with disabled intelligent beam tracking ability.

From the test results shown in Fig. 2.5 (with disabled intelligent beam tracking), a degradation due to wind (blue circle when red line was constant and blue line dropped due to antenna quick movement by wind gusts) and due to solar radiation (red circle when both lines slowly moved up and down simultaneously) of approximately 20 dB was observed.

In contrast, Fig. 2.4 shows a stable link performances with the RSL fluctuation in a range of 3 dB when the intelligent beam tracking ability was enabled.

Annex 3

**Link budget evaluation**

Herein, the effects of atmospheric environment, including atmospheric attenuation, rain attenuation, and wind, on fixed wireless links are evaluated. Examples of link budget evaluation in terms of signal-to-noise ratio and maximum channel capacity for fixed point-to-point wireless links are described.

1. **Clear atmospheric attenuation**

Even in a clear atmosphere the electromagnetic waves are attenuated owing to oscillations of atmospheric gas and water molecules initiated by the electromagnetic waves. Since these molecules are a basic part of the atmosphere, this attenuation cannot be avoided. The amount of the attenuation in the clear atmosphere depends on the frequency difference between the electromagnetic wave and the resonance of the molecules. If the frequency of the wave coincides with the resonance frequency, the attenuation becomes a relative maximum.

The gaseous attenuation *Agas* (dB) is calculated following the ITU-R Recommendation P.676 as follows:

where *f* is the carrier frequency, *r0*is the transmission distance, ** is the specific attenuation which is the accumulation effect from oxygen (or dry air, *o*) and water vapor (*w*). *N’’(Oxygen)(f)* and *N’’(Water Vapor)(f)* are the imaginary parts of the frequency-dependent complex refractivities which can be expressed as follows,

where *Si* is the strength of the *ith* oxygen or water vapor line, *Fi* is the line shape factor of the oxygen or water vapor, *N’’(D)(f)* is the dry continuum from pressure-induced nitrogen absorption which can be expressed by,

where the parameters are described as follows,

Other parameters inside *Si*, *Fi* and *N’’(D)(f)* functions are as follows,

Using equation (3.1), clear atmospheric attenuations for different transmission distances in a standard atmosphere (temperature of 288.15 K and air pressure of 1013.25 hPa) for fixed wireless links at carrier frequencies 75.375 and 85.375 GHz are calculated as shown in Fig. 3.1.



Figure 3.1. Clear atmospheric attenuation.

1. **Rain attenuation**

The attenuation due to rain *Arain* (dB) can be calculated using the ITU-R Recommendation P.838 as follows,

where *r0*is the transmission distance, *R* is the rain-related specific attenuation, *R* is the rain rate (mm/h). Parameters *k* and ** can be calculated from the following equations:

where:

The rain attenuations of fixed wireless links using carrier frequencies at 75.375 and 85.375 GHz for different distances are shown in Fig. 3.2.



Figure 3.2. Rain attenuation of fixed wireless link.

1. **Wind effect**

The performance degradation due to wind of a fixed wireless link using a general pole structure is described by in Annex 1. Other types of structure have different parameters and wind gusts will have other consequences on the received power attenuation. Here, to give an example of applying the model in the link budget calculation, we present the calculation for a specific pole structure with the coefficients described by Case 2 in Table 1.2 of Annex 1. For other types of pole structure, it is possible to apply the model for the calculation by using corresponding coefficients that represent the structure.

As described in Annex 1, when concerning the wind effect, the static inclination angle due to wind can be expressed as follows,

Where the coefficients for the specific case described in Table 1.2 of Annex 1 are as follows,

In addition to static inclination angle, the pole also vibrates by wind at a natural frequency of 2.3 Hz, which results in a dynamic inclination angle. The dynamic inclination angle *d* can be expressed as,

where *Cd* is the dynamic wind load coefficient. Additionally, the initial alignment error *0* also affects the inclination angle. Therefore, the accumulated inclination angle can be expressed by,

The wind speed is related to probability which can be expressed by the Weibull distribution as follows,

Using the mentioned equation, a maximum wind speed of 17.8 m/s can be obtained for an accumulated probability of 99.999%,

Considering the parameters of Case 2 in Table 1.2 of Annex 1, the inclination angle for this specific case can be calculated as,

The overall inclination angle owing to wind effect can be calculated to be 0.4314 deg for a maximum wind speed of 17.8 m/s. Figure 3.3 shows the rms value of the inclination angle with respect to the wind speed in a measurement system. The calculated inclination angle from above mathematical models without the initial alignment error *0*is also included in the figure, showing a good agreement with the measured data. Notably, the small difference between calculated and measured data could be attributed to the fact that the measurement system might include an initial alignment error.

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| グラフィカル ユーザー インターフェイス, グラフ  自動的に生成された説明 |
| Figure 3.3. Measured inclination vs. wind speed and calculated values. |

Next, as described in Annex 1, the gain degradation *G()* due to wind effect can be expressed by,

where

Using the mentioned equations, the gain and gain degradation of the antenna with wind effect at different carrier frequencies are calculated as follows,

In addition to the gain degradation by wind effect, as shown in Fig. 1.5 of Annex 1, the received signal level would also be degraded by an additional amount owing to natural vibration, which was not considered in above mathematical models. In the link budget calculation, thus, an additional link margin of 5 dB is reserved to compensate for the gain degradation by natural vibration.

1. **Signal-to-noise ratio of fixed wireless links**

The received signal-to-noise ratio (SNR) can be calculated as,

where:

F (dB): noise figure of the system, which is assumed to be 10 dB in the calculation.

The free space loss and thermal noise can be expressed by,

where:

Using the previously described formulas and parameters, the received SNRs of a fixed wireless link can be calculated for different cases as follows,

* Case 1: no wind effect

In this case, only attenuation due to clear atmosphere and rain are considered. The calculated SNRs for fixed wireless links at 75.375 or 85.375 GHz are shown in Figs. 3.4 (a) and (b), respectively. A channel bandwidth of 2.16 and 4.32 GHz is considered in this calculation.

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| 1. Figure 3.4. (a) SNR vs. transmission distance for 75.375 GHz link (without wind effect). | 1. Figure 3.4 (b). SNR vs. transmission distance for 85.375 GHz link (without wind effect). |

* Case 2: wind effect at both transmitter and receiver antenna

In this case, all the attenuations by clear air, rain, and wind are considered. For the wind effect, a gain degradation of 2.6728 or 3.4859 dB are calculated for each antenna at the carrier frequency of 75.375 or 85.375 GHz, respectively. In addition, an additional margin of 5 dB is reserved to compensate for the natural vibration by wind effect. The received SNR are shown in Figs. 3.5 (a) and (b).

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| Figure 3.5 (a). SNR vs. transmission distance of 75.375 GHz link (with wind effect). | Figure 3.5 (b). SNR vs. transmission distance of 85.375 GHz link (with wind effect). |

1. **Maximum channel capacity of fixed wireless links**

The fixed wireless link is linear and can be seen as an additive white Gaussian noise channel. In such a channel, the maximum channel capacity is defined by its capacity which can be calculated with the Shannon formula as,

where is the available bandwidth of the channel.

Using the calculated SNRs described above, the expected maximum channel capacity can be estimated as shown in Figs. 3.6 (a) and (b) for the case of without wind effect and Figs. 3.7 (a) and (b) with wind effect. The channel bandwidths in these calculations are 2.16 and 4.32 GHz.

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| Figure 3.6 (a). Maximum channel capacity vs. transmission distance for 75.375 GHz link (without wind effect). | Figure 3.6 (b). Maximum channel capacity vs. transmission distance for 85.375 GHz link (without wind effect). |
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| Figure 3.7 (a). Maximum channel capacity vs. transmission distance for 75.375 GHz link (with wind effect). | Figure 3.7 (b). Maximum channel capacity vs. transmission distance for 85.375 GHz link (with wind effect). |