



E- and V-Band Millimeter-Wave Technology for High-Capacity Wireless Communications: A Comprehensive Review of Advancements, Challenges, and Point-to-Point Link Planning

¹Rakesh Kumar, ²Sudeep Baudha

^{1,2} Department of Electrical and Electronics Engineering, Birla Institute of Technology and Science, Pilani, K K Birla Goa Campus, Zuarinagar, Sancoale, Goa 403726, India.
Email: ¹p20240515@goa.bits-pilani.ac.in, ²sudeepb@goa.bits-pilani.ac.in

Abstract

Telecommunication networks are rapidly evolved with 4G and 5G technologies. This has resulted in data explosion and immensely increased data consumption that require fibre connectivity like data capacity with every base station which is a challenge due to various issues like ROW permission and cost. Traditional frequency bands from 7 GHz to 23 GHz have a very limited spectrum and are capable of providing capacities up to few hundred Mbps only. E and V frequency bands in mmW technology have an enormous spectrum and are capable of providing fibre like capacities wirelessly. This review paper covers over-view, architecture, and application of E and V band technology, step-by-step process to plan a link, gaps in existing research, and scope for further research in future. It analyses the capabilities, limitations, advancements, challenges and performance matrix. A detailed comparison of E and V band with traditional frequency bands is also presented to facilitate the understanding with benefits and risks of mmW technology. Additionally, a step by step link budget and planning for deployment of E band radios in a telecommunication network is covered which is much simpler with novel planning approach. Overall, this review paper is an attempt to provide holistic view about present E and V band mmW technology for high capacities wireless communications point-to-point link and future research prospects to further improve it.

Keyword: 4G, 5G, millimeter Wave (mmW), E-Band, V-Band, Line-of-Sight (LOS), backhaul, short-haul, latency, parabolic antenna, Quadrature Amplitude Modulation (QAM), reliability, fade margin, receiver sensitivity.

Introduction & Motivation: Data Explosion

With the rapid change in technology from 3G to 4G and now 5G, immense growth in data traffic has been seen in the past couple of years. This growth will further continue as the 5G deployment is being enhanced at lightning speed. Over 400,000 base station to provide 5G network have been deployed in India till end of 2025 which is the highest in the world. As per Mobile Data Traffic Outlook by Ericsson [1], global data traffic increased yearly at 30% from 55 EB per month in 2020 to 201 EB per month in 2025. This rise in data consumption is expected to continue and reach 474 EB per month in 2030 at an average yearly growth rate of 16%.

TABLE 1: Global Data Consumption and Growth Estimate

Year	Global Data Consumed (EB/Month)	% Yearly Growth
2020	55	
2025	201	30%
2030	474	16%

EB – Exabyte = 1×10^{18} byte

Data speed per subscriber is expected between 10 to 100 Mbps with 4G technology which is increased to 1 Gbps when mobile networks are equipped with 5G technology. This technology shift from 3G to 4G and now to 5G has forced the network planners to enhance the capacity of backhaul transport by many fold so that committed data speed per user can be delivered seamlessly to provide good network experience. With 5G technology, the backhaul capacity for each base transceiver station (BTS) is around 10Gbps in urban and dense urban region and 1 Gbps to 4 Gbps in sub-urban and rural areas [5], [25], [28], [36] Fiber optic networks can easily deliver such a high requirements of transport networks. However, due to geographical limitations and cost factors, it is not feasible to lay fiber cable to connect every base station. Only around 40% of total over 7 million base stations world-wide are fiberized till date. Remaining 60% base stations are still surviving and depending on the microwave transmission only. Unfortunately, microwave links designed with traditional frequency bands i.e. 7, 8, 11, 13, 15, 18 & 23 GHz can provide limited throughput up to 400 Mbps by dual polarized systems using single RF channel of 28 MHz bandwidth. Telecom operators and service providers are looking for options beyond traditional frequency bands that can achieve ultra-high capacity requirements of point to point wireless backhauling to connect base stations where fiber connectivity is none-viable.

To transcend this throughput limitation of traditional microwave links, millimetre wave (mmW) technology in E and V frequency bands provide solutions to backhaul ultra-high throughput of 4G/5G base stations to core networks where fiber connectivity is not viable [40].

Purpose: The aim of this review study is to explain the E&V band mmW technology with its advantages and disadvantages including advancements. Additionally, due to high rain attenuation in E & V band frequencies, the transmission planners are afraid of using E band mmW links independently for unacceptable link outages. Traditional frequency band radios are used in parallel to E-band radios and even on longer hops over 5 Km. This increases the cost of deployment and limits the usage of E-Band technology effectively. This paper clearly explains the link design process and list out guidelines and various practical technics can be used in the field for successful deployment with acceptable reliability of E Band mmW radio links.

This paper is organized as follows. **Section II** describes the overview of E & V Band technology comprising definition and frequency ranges of E & V Bands, Radio Architecture & Building Blocks, and comparison with traditional microwave frequency bands. **Section III** covers advancements in E & V Band in terms of key parameters and comparison with traditional microwave frequency bands. **Section IV** gives link and power budget planning with description of various parameters and step by step process and mathematical model for power budgeting, capacity and availability calculations. **Section V** explains important key performance indicators (KPI) and matrix. Few sample links power budgeting and link planning with field performance evaluation is covered under **Section VI**. Challenges in deployment and a novel planning approach for E-band are given in **Section VII**. Gaps in present technology and further scope for research areas are also explained in **Section VIII**. At the end, conclusion is drawn in **Section IX**.

OVERVIEW OF THE E & V BAND TECHNOLOGY

Definition: Wavelength of frequency ranges between 30GHz and 300GHz is below 10 millimeter but above 1 millimeter. So, radio technology designed to operate in this frequency ranges are, generally, called millimeter-wave (mmW) technology. E-Band and V-Band frequency ranges [2], [3], [25] falls within millimeter wave spectrum as shown in Table 2 and Figure 1 below.

TABLE 2: Frequency Ranges of E & V Band

	E-Band	V-Band
Frequency Range	71 - 86 GHz	57 - 64 GHz
Wavelength	4 mm	5 mm

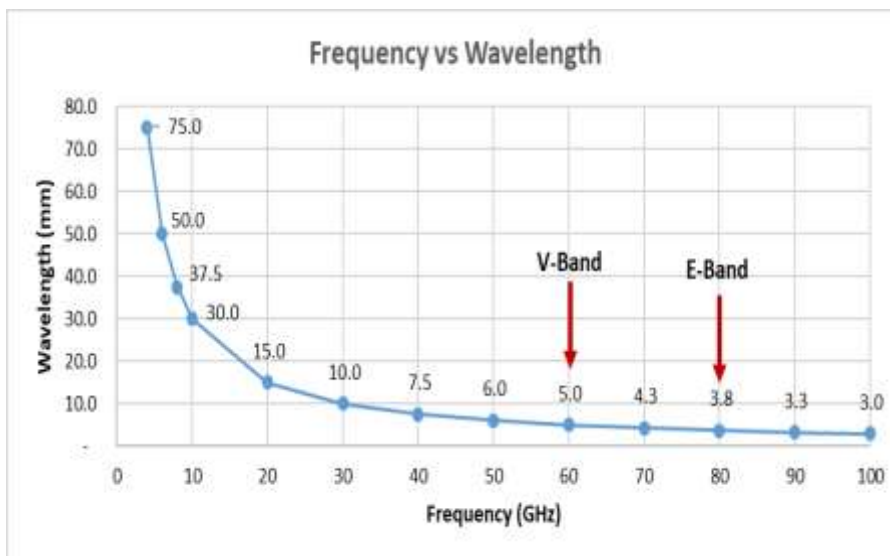


FIGURE 1: Frequency vs Wavelength

Benefits: E and V frequency bands offer various benefits such as:

- RF channel bandwidth is much higher in E and V frequency bands compared to traditional microwave bands. For example: One RF channel bandwidth in E-Band is 250 MHz [2], [3], [25] while it is only 28MHz in traditional bands i.e. 7 – 23GHz frequency bands which is over nine times. Based on the wider RF channel, the data capacities provided by E and band are accordingly multi-fold compared with traditional ones.
- Reuse distance of RF channels is very small because propagation losses of E and V band frequencies are much higher (refer figure 2) [11].
- Cost of ownership is much less than the fiber network [13].
- Rapid deployment is another benefit of the radio systems when compared with fiber networks which takes much longer time to commission [13].
- E and V band radios have small form factor due to small wavelength and antenna sizes.

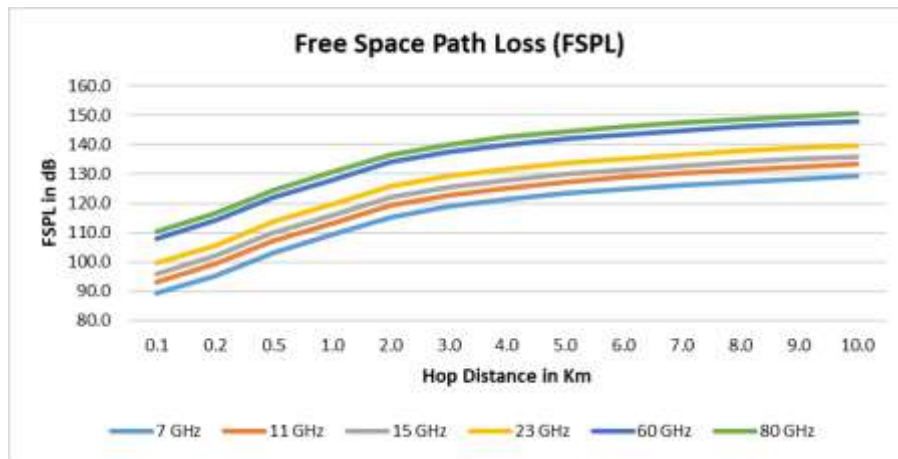


FIGURE 2: Free Space Path Loss (FSPL) vs Hop Distance for 7 – 80 GHz frequency

Various Components of mmW Radio: The architecture of mmW radio is almost similar to traditional microwave radios. They typically include a modulator, transmitter, receiver, demodulator and an integrated antenna. The form factor is smaller and encapsulated in an outdoor unit. The Typical architecture is shown in figure 3.

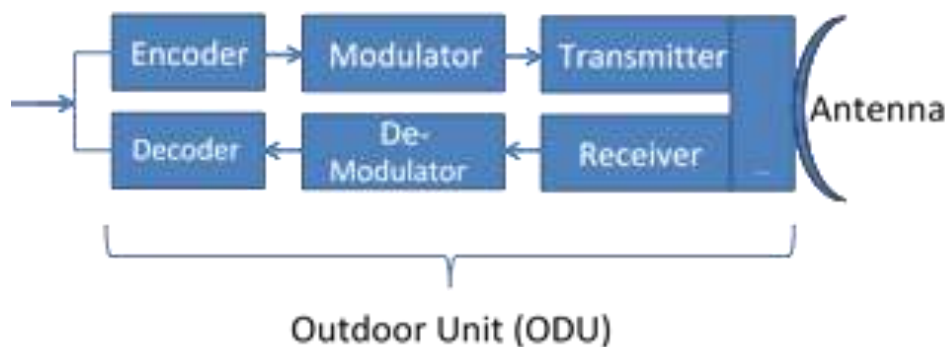


FIGURE 3: Typical E / V Band Radio Architecture

The very compact E-band radio front end module integrated with antenna can be built by using gap waveguide technology [49]. Additionally to multiplex multiple channels, an E-band multiplexer designed based on Turnstile Junction [47] which provides very low insertion loss lesser than 1.7 dB. The detailed block-diagram of a compact E-band radios is mostly adopted by the industry as given in [85]. More innovations on radio architecture and modules are further added under Section III.

Application: There are numerous use cases of E & V-band point to point links. Some of the main applications are listed below [5], [6], [12], [13], [25], [26], [36], [40]-

- In 5G networks, E/V-band point-to-point links are used to connect small cells with the core network for back-hauling in urban areas [95].
- E-band radios are successfully tested to provide solution for wireless fronthaul [86], [95].
- These radio links are also used extensively in dense urban regions where distances are short and capacity requirements are high.
- Where fiber deployment is not feasible and capacity requirements are high, E/V-band mmW link is an ideal solution.
- E-band mmW links are used as Fronthaul connectivity between baseband unit and RF unit thereby avoiding cable between the two. Analog wireless fronthaul link is implemented and demonstrated at 70/80 GHz (E-Band) for 20 MHz 64-QAM LTE transmission, equivalent to 1.25 Gbps digital CPRI traffic [55].
- For fiber extension wirelessly using E/V-band mmW links, high capacities are delivered to the enterprise customers to meet their requirements.
- High capacity reliable internet connection to a business unit is easily, quickly and cost-effectively delivered using E/V-band mmW link.
- To broadcast live sports events or video transmission, E/V-band radios can be used very effectively to provide connectivity between a stadium and the fiber POP that is connected to broadcast studio and control room.
- To connect two high rise buildings across the busy road, E/V band radios can provide an extremely reliable, high capacity solution at a very low cost compared with fiber deployment.
- These technologies can be used to provide ultra-high speed connectivity to serve any sector i.e. entertainment, education, healthcare, industry, surveillance, etc. where fiber-like capacities are needed but fiber viability is not ensured.
- Used as a backup link to fiber network to ensure network availability when fiber networks are failed due to fiber cuts or equipment failures.

More detailed study of both E & V bands is done in subsequent topics of this paper which will establish the benefits and limitations of each frequency band.

ADVANCEMENT IN E/V BAND

With the data explosion due to 4G and 5G network rollout and high smartphone penetration among subscribers, E-and V frequency bands proved to be a boon to the telecom service providers to ensure very good network experience to its subscribers. Incredibly higher RF bandwidth to provide fiber like capacities, very low latency, small form factor due to millimeter wavelength, and frequent reuse of same RF channel as a result of higher propagation loss, E and V band have successfully demonstrated many advancement in the point to point connectivity and become life-line of mobile networks in the absence of fiber connectivity. We will discuss new developments in GaAs microwave ICs, front-end modules, and spectral efficiency enhancements, improvements in antenna, key parameters, and comparison with traditional frequency bands.

High data rates of 12 Gb/s over a RF bandwidth of 4GHz is achieved using spectrally efficient frequency division multiplexing (SEFDM) implemented using GaAs microwave integrated circuits in E-band [52]. A bi-directional photonics-added mmW radio over fiber (MMW-RoF) transmission system at E-band was demonstrated experimentally with a net transmission rate of 45.38 Gb/s in each direction using entropy of 10bit/symbol/Hz with TPS-4096QAM [53]. Another demonstration has achieved 91.46 Gbit/s by using 4096QAM OFDM signal at E-band frequencies with the help of probabilistic shaping (PS) and Volterra nonlinearity compensation (VNC) technology [56].

A wideband intermediate frequency (IF) module with transceiver (TRX) function for E-band applications is developed to realize high capacity. The proposed IF module consists of four paths, which are combined by a combiner in the transmit channel and separated by a splitter in the receive channel. For each path, it includes an amplifier, mixer and a variable gain amplifier as well as two stage filters. The dynamic range for both receiving and transmitting path are 31.5dB and predicted noise figure (NF) of receiving path, including frontend, is 4.29dB [82].

A compact module consisting of a novel integration of an antenna, a diplexer, and millimeter-wave active circuits for low latency and multi-Gbit/s capacity wireless backhaul links working at E-band are developed using the gap waveguide technology [83], [84].

Using the orbital angular momentum (OAM) multiplexing technique in E-band, field experimental results indicate successful real-time transmission of 139.2 and 104.0 Gb/s at distances 22.5 and 45m [57]. Achieved 55.6 bps/Hz spectral efficiency and 139 Gbps data rate over 1.5-Km LOS link by using 8x8 MIMO and 256QAM technology [54]. 65 nm CMOS technology is used to design a direct conversion transmitter at E-band for 1024 QAM [58]. Similarly, an E-band receiver is designed with 55 nm SiGe BiCMOS technology which allows reaching a high level of integration. The receiver is based on Low Noise Amplifier (LNA), Variable Gain Amplifier (VGA) and a double balanced mixer provides I/Q baseband outputs [59]. A wideband and high-linearity E-band transmitter integrated in a 55nm SiGe technology that gives output power of 16.8dBm and successfully demonstrated the transmission of 10.12 Gb/s 64-QAM signal with a spectral efficiency of 5.06 bits/s/Hz [63]. Likewise, E-band transceiver circuits in a super-heterodyne architecture covering lower 71-76 GHz and upper 81-86 GHz bands were designed and fabricated in 0.13 micro-meter SiGe technology [61]. Another hardware efficient implementation of a digital baseband receiver using analog symbol timing recovery (STR) block and a digital carrier recovery block in E-band and tested in laboratory conditions which supports 5 Gb/s data traffic with 16QAM modulation [60]. A metallic 3-D printing technology is used to implement an E-band radio front end composed of two band pass filters and a conical horn antenna. This technology proves its great potential for mmW applications [62]. A novel technology implemented for an E-band transceiver using Microstrip and Waveguide SMT Package (MWgSP) which successfully integrates circuits of up-converter and low noise down-converter reducing both material and manufacturing cost [64]. E-band radio development relies heavily on a multi-chip module approach using off-the-shelf MMICs. However, there is a potential to develop a new single chip integration topology for E-band radio [65]. Recent developments in semiconductors for E-band radio are to achieve ultra-low noise LNA with noise figure of 4.5dB, high transmit output power up to 27dBm, 32-way in-line power combiner for high power MMIC amplifiers, and realization of various building blocks of E-band radios using emerging GaN technology for next-generation mmW radio applications [66] – [69].

Remarkably, numerous developments have been done in antenna side for E-band point-to-point gigabit communications. Some of the important design and developments are mentioned here: A cylindrical reflector antenna is designed to operate in E-band which provides the gain of 41.4dBi with 60% aperture efficiency. This is easier and cheaper to manufacture compared with normal parabolic dish reflector antenna [71]; A high gain compact size horn lens antenna (area of 95.12mm x 95.12mm x 6.35mm) to operate at E-band is fabricated using printed circuit board (PCB) designed to provide gain of 35 dBi with aperture efficiency of 47.6% [72]; Another design is 2-D beam-steerable integrated lens antenna with capability of continuous beam-switching range of about 8 deg x 34 deg and achieved directivity of 36.7 dB to operate at E-band [73]. This is very useful feature to provide a stable link performance because the beam-widths at e-Band are very narrow and antennas are mis-aligned and links become un-stable in case of high-wind velocity conditions; another beam-switching dual-spherical lens antenna with low scan loss (below 1.3dB) to operate at E-band is designed and achieved the gain of 21.8 dBi [75]; similarly a 2x8 array for E-band is designed using a substrate-integrated waveguide (SIW) and a short circuited metallic via inserted inside the ring slot on a 0.5mm thick Rogers5880 substrate and fabricated using low cost PCB process and achieved 50% radiation efficiency [74]; Another design is compact size Y-shaped broadband antenna for E-band applications is realized as a single-layered micro-strip antenna that achieves 8.77 dBi gain and successfully tested for MIMO array

configuration of four elements [76]; Another interesting antenna design is Axial Displaced Ellipse (ADE) reflector antenna with adjustable beam-width (can be increased without beam bifurcation by more than 250%) for E-band point-to-point wireless link which achieved the gain of 46.1 dBi [77]; One more development in E/V frequency band has proposed a modulated geodesic lens antenna with the scanning abilities in both azimuth & elevation and array of four lens antenna elements, and each element produces 13 independent beams that cover 110 degree in H-plane with scan loss below 1 dB and realized gain variation between 20.8 and 24.1 dBi [78]; Very recently, a new 50 dBi E-band dual-reflector antenna with auto-beam-tracking function is designed and achieved by defocusing the feed away from the focus point of the sub-reflector, while keeping the interface with the transmit-receive unit stationary by applying a movable gap-waveguide configuration [79].

E-band frequencies are severely affected by the rain attenuation which need to be taken care while designing the control algorithm of the adaptive modulation system so that the modulation shifts to lower modulation in case the real time rain rate breaches the defined threshold. Data from rain gauge sensor is employed to improve the performance of the data transmission through E-band link [80].

A 3-D printed lightweight miniaturized dual-band dual-polarized feed module for advanced millimeter-wave (E-band) and traditional microwave shared-aperture conical horn radiator antenna is developed using air-filled waveguide orthomode transducer (OMT) which demonstrated excellent performance in terms of wide bandwidths, high isolations of greater than 40dB, high radiation efficiency of about 90%, and stable dual polarized radiation patterns with low cross polarization [80]. This is very where both E-Band and traditional microwave links can be installed on a long haul backhaul using single antenna system hence saving the cost and space on the towers.

Key Parameters of a Point-to-Point Link: Data throughput and latency are the main parameters to evaluate any transmission technology and products. However, wireless technology can be evaluated from many angles such as performance during rains, interference handling, frequency reusability, antenna gain vs size, form factor, energy efficiency, cost effectiveness, etc.

Comparison with traditional frequency bands: Table 3 gives comprehensive comparison of various important parameters among E, V and traditional frequency band of 15 GHz [40]. Following nomenclature are used in the table 3 –

- Parameters highlighted in dark green are best.
- Parameters highlighted in light green are better.
- Orange highlighted parameters are poor in E & V band.
- Red highlighted ones represent biggest disadvantage.

Accordingly, the inferences of various parameters' comparison from the table can be made as:

1. Huge spectrum is available in E & V frequency bands in comparison to traditional bands.
2. Throughputs up to 24Gbps in E-Band [26] and 5 Gbps in V-Band can be achieved if we use eight channels and XPIC (Cross-Pole Interference Cancellation) together.
3. Higher modulations up to QAM-4096 can provide further increase in throughput by around 20%. QAM-512 and above modulation levels are not used generally because complexities increases with increase of every additional bit in a symbol and degrades the receiver sensitivity; and this reduces effective hop length significantly. Therefore, QAM 256 is very safe and acceptable modulation level industry wide.
4. Latency is also significantly lower to the tune on 10 milliseconds and 20 milliseconds.
5. Fresnel zone radii are halved or further lowered which helps in the establishment of Line-of-Sight (LOS) links even in narrow lanes and densely populated urban areas.
6. Antenna gains are 12 to 15 dB better which confirms the use of smaller size antenna. It means the overall form factor of the E band and V band radios will be smaller compared with traditional frequency band radios.
7. Free space path loss (FSPL) is 12 to 15 dB higher in V and E band for a given hop length (refer Figure 2) which reduces the usable hop length significantly compared with the traditional frequency band.
8. There is an additional attenuation of about 15dB/km in V-band frequencies due to oxygen and water vapour contents in the atmosphere. Therefore, the V-band links are restricted for use beyond 1.0 km hop lengths. These are generally preferred for indoor applications.
9. With reference to above point viii, E-Band is most preferred and popular for use in telecommunication networks for hop distances of few kilometres i.e. below 3 Km [26], [27], [37].

TABLE 3: Comparison of Key Parameters

S/N	Key Parameter	E-Band	V-Band	Traditional Bands*	References
1	Frequency Range (GHz)	71 - 76 & 81- 86	57 - 66	14.5 - 15.35	[2], [3], [4], [8], [9]
2	Spectrum Available	12 GHz	9 GHz	< 1 GHz	
3	RF Channel Bandwidth	250 MHz	50 or 56 MHz	28 MHz	
4	Modulation	256 QAM	256 QAM	128 QAM	[3]
5	Throughput (Gbps)				
5.1	Single RF Channel	1.5 Gbps	340 Mbps	155 Mbps	Table 11, Table 12
5.2	Four RF Channels	6.0 Gbps	1.3 Gbps	N/A	
5.3	Eight RF Channels	12.0 Gbps	2.5 Gbps	N/A	
5.4	XPIC Configuration	x2	x2	x2	
6	Latency (usec)	<10 msec	<20 msec	<50 msec	
7	Transmit Power (dBm) - Typical	+30 dBm	+10 dBm	+27 dBm	[2], [3]
8	Receiver Threshold (dBm) - Typical	-66 dBm	-66 dBm	-69 dBm	Table 8
9	Free Space Loss Path (FSPL) for 5Km Hop	144.5 dB	142 dB	130 dB	Table 5
10	Rain Attenuation (@rain rate - 63mm/hr)				
10.1	Vertical Polarization	21.40 dB/Km	18.93 dB/Km	3.79 dB/Km	Table 6
10.2	Horizontal Polarization	22.31 dB/Km	20.53 dB/Km	4.71 dB/Km	Table 7
11	Atmospheric Attenuation due to Oxygen & Water Vapor (dB/Km)	< 1	15	< 1	[6], [7]
12	Hop Lengths	< 3.0 Km	< 1 Km**	< 15 Km	[10]
13	Fresnel Zone (F1) in meter				
13.1	Hop Length - 1Km	0.97	1.12	2.23	Table 13
13.2	Hop Length - 3Km	1.68	1.94	3.87	
13.3	Hop Length - 5Km	2.16	2.50	5.00	
14	Antenna - Parabolic Dish				
14.1	Gain (dBi)				
16.1.1	0.30m	44.99	42.49	30.45	Table 4
16.1.2	0.60m	51.01	48.51	36.47	
14.2	Half Power Beamwidth (deg)				
16.2.1	0.30m	0.75	1.00	4.00	Table 4
16.2.2	0.60m	0.38	0.50	2.00	
*	Traditional band of 15GHz is considered.				
**	V-Band hop length is impacted because of additional attenuation by oxygen and water vapor.				

LINK PLANNING AND POWER BUDGET

This section discusses the step by step process for designing a link between the two sites which involves various mathematical formulas and calculations. For illustration purposes, we have considered a case of E-Band mmW link and included information for V-band as well wherever it seems feasible for comparison purposes.

In a point to point communication, two sites on the earth i.e. Location A and Location B can be connected using an E-band mmW link if line-of-sight is established between both the points. This is called a link or a hop in general. Refer to Figure 4 for better understanding of a link and its various components.

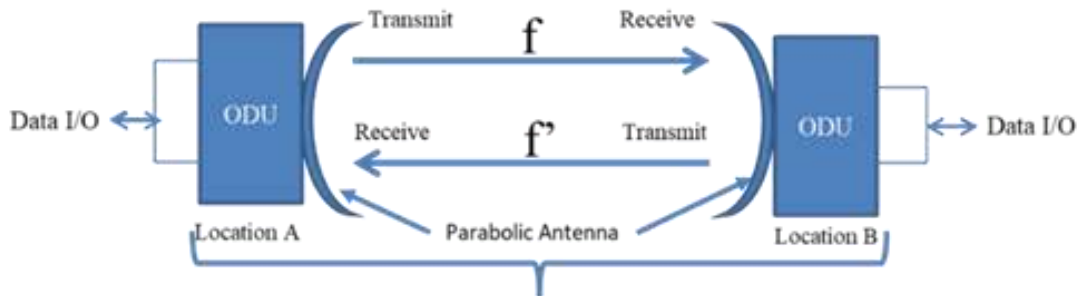


FIGURE 4: A Typical Link or Hop

To design a LOS link to achieve the required performance in terms of throughput, bit error rate (BER) of 1E-6 and link uptime or availability in a telecommunication network, the following steps and parameters as defined in various ITU-R P-series recommendations [16] and other references [38], [39], [40], [44], [46], [93] and various transmission losses [15] are considered:

- **Transmit Power and EIRP:** Maximum transmit power is defined by ETSI in terms of EIRP (Equivalent Isotropic Radiated Power) which is a product of transmit power and transmit antenna gain as given in equation 1 [2], [3].

$$\text{EIRP (dBm)} = \text{Transmit Power (dBm)} + \text{Transmit Antenna Gain (dBi)} \tag{1}$$

Maximum EIRP is +85dBm for E-Band and +82dBm for V-band as per ETSI. Based on the EIRP limits, maximum transmit power for both E and V bands are limited to one watt (+30 dBm). However, the industry has agreed to design mmW radios with typical transmit power of 100mW (+20dBm) for both frequency bands. However, high power options up to 1 watt (+30dBm) are also made available to meet link budget requirements to mitigate high rain attenuations in tropical and coastal regions with extremely high rain rates. Automatic Transmit Power Control (ATPC) and Remote Transmit Power Control (RTPC) features are generally provided by all the equipment manufacturers. These functionalities are very useful to mitigate the interference and rain fading effect to achieve target availability [32], [33], [34], [35]. This makes the radio system very power efficient.

➤ **Transmit and Receive Antenna Size and Gain:** Parabolic dish antennas are used for transmitting and receiving signals in a point to point mmW link. The gain of an antenna depends on the size of the reflector and the frequency of operation. The following equation 2 [14], [22] is used to calculate the antenna gain in dBi –

$$\text{Antenna Gain (dBi)} = 10 \log \{k * (\pi * D / \lambda)^2\} \quad (2)$$

Where D = Antenna Diameter in meter; λ = Wavelength in meter
 k = Efficiency which is around 50% achievable practically

These antenna have very narrow pencil beam. Half-power beam width (HPBW) in degree can be calculated by using the formula of equation 3 [14]-

$$\text{HPBW (deg)} = 60 * (\lambda / D) \quad (3)$$

Where D = Antenna Diameter in meter; λ = Wavelength in meter

Using equations 2 and 3, the antenna gain and HPBW are calculated for 0.3 and 0.6 m antenna sizes [27], [37] and given in table 4.

TABLE 4: Antenna Gain and HPBW

Antenna Size (m)	E-Band		V- Band	
	Gain (dBi)	HPBW (deg)	Gain (dBi)	HPBW (deg)
0.3	44.99	0.75	42.49	1.00
0.6	51.01	0.38	48.51	0.50

A few thumb rules are noted from the table for easy calculations in the field to estimate antenna gain and HPBW for any other size of antenna –

- If the size of antenna is doubled or halved, the gain increases or decreases by 6 dB respectively
- HPBW reduces to half when antenna size is doubled and becomes double when antenna size is halved.

Another interesting point to note is that the HPBW is only half a degree and even lesser for 0.6m antenna which is extremely narrow and makes antenna alignment difficult. Therefore, OEMs provide an antenna alignment tool built-in into the radio to assist field engineers in alignment. Also, antennae beyond 0.6m diameter are not recommended for practical use. Antenna can be used as either vertically polarized, or horizontally polarized. Both polarizations are used when XPIC configuration is planned. 30 dB isolation between vertical and horizontal polarization is easily achieved in the available products.

➤ **Free Space Path Loss (FSPL):** The losses due to attenuation of the radio signal as it travels through the space are called free space path loss (FSPL). It depends on the frequency and path distance. In compliance with ITU-R P.525 recommendations [11], [14], [22], [37], [38], [95]. FSPL is calculated using equation 4 as given below.

$$\text{FSPL (dB)} = 92.45 + \log D + \text{Log F} \quad (4)$$

Where D = Hop Length in Km; and F = Frequency in GHz

Table 5 below gives the FSPL values for E, V and traditional frequency bands for varying hop lengths starting from 100 m to 10 km.

TABLE 5: FSPL for Traditional, V and E Frequency bands

Distance (Km)	Free Space Path Loss (dB)					
	Traditional Microwave Frequency Bands (GHz)				V-Band (GHz)	E-Band (GHz)
	7 GHz	11 GHz	15 GHz	23 GHz	60 GHz	80 GHz
0.1	89.4	93.3	96.0	99.7	108.0	110.5
0.2	95.4	99.3	102.0	105.7	114.0	116.5
0.5	103.3	107.3	110.0	113.7	122.0	124.5
1.0	109.4	113.3	116.0	119.7	128.0	130.5
2.0	115.4	119.3	122.0	125.7	134.0	136.5
3.0	118.9	122.8	125.5	129.2	137.6	140.1
4.0	121.4	125.3	128.0	131.7	140.1	142.6
5.0	123.3	127.3	130.0	133.7	142.0	144.5
6.0	124.9	128.8	131.5	135.2	143.6	146.1
7.0	126.3	130.2	132.9	136.6	144.9	147.4
8.0	127.4	131.3	134.0	137.7	146.1	148.6
9.0	128.4	132.4	135.1	138.8	147.1	149.6
10.0	129.4	133.3	136.0	139.7	148.0	150.5

FSPL values of Table 5 are also presented in graphs in Figure 2 for a better understanding of frequency and distance relation. Interesting points in this domain which are useful for field engineers to use as thumb rule are noted below:

- FSPL is significantly higher to the tune of 12 to 20 dB for V and E band when compared with traditional bands.

- FSPL is increased by 6 dB when the path length is doubled and gets reduced by 6 dB when path length is halved.
- In case the hop length is increased by 10 times, the FSPL is increased by 20 dB.
- Similarly, FSPL is increased by 6 dB when the frequency is doubled and it is reduced by 6 dB when the frequency of operation is halved.

➤ **Rain Attenuation:** The wavelength at E and V bands is only 4 to 5mm which is much smaller than the rain droplets. Hence, when these signals pass through the rain droplets, they experience high attenuation. That is the reason why the reliability of E and V band mmW radio links are greatly impacted due to rains. The specific rain attenuation A_R is calculated from the rain rate (in mm/hr) using a power-law relationship as given below in equation 5 according to ITU-R P.838-3 recommendation [18] and other references [24], [37], [38].

$$A_R = k * R^\alpha \quad (5)$$

Where k & α = coefficients are polarization and frequency dependent as given in the ITU-R P.838-3 recommendation for horizontal and vertical polarizations separately for operational frequency which is E and V band.

$$R = \text{Rain rate in mm/hr}$$

R is a rain rate parameter in mm/hr differentiating the intensity of rainfall. This can be obtained from a set of specified values for different regions as given in ITU-R P.837-7 recommendations [19]. Rain attenuation for a path length D can be obtained using equation 6.

$$A_{0.01} = A_R * D_{\text{eff}} \quad (6)$$

Where $A_{0.01}$ is rain attenuation for path length D if rain rate exceeded for 0.01% of time.

And D_{eff} is the effective path length of D which can be calculated by using equations 7, 8 & 9.

$$D_{\text{eff}} = r * D \quad (7)$$

Where D is path length or hop length. And r is reduction factor.

$$r = 1/(1+D/d_0) \quad (8)$$

$$d_0 = 35 * e^{-0.015R} \quad (9)$$

[in case of $R_{0.01} > 100$ mm/hr, use 100 for $R_{0.01}$]

The total path attenuation due to rain exceeding 0.01% of time can be calculated using equation 10 which is a resultant equation derived from equations 5, 6, 7, 8 and 9.

$$A_{0.01} = A_R * D * r \quad (10)$$

Rain attenuation for various rain rates and frequencies from 7 to 80 GHz are presented in Tables 6 and 7 with their corresponding graphs in Figure 5 and 6.

TABLE 6: Attenuation in dB/Km for Vertical Polarization

Vertical Polarization					
Frequency	Rain Rate (mm/hr)				
	42	63	95	115	145
7 GHz	0.35	0.64	1.17	1.56	2.19
11 GHz	1.33	2.13	3.43	4.29	5.61
15 GHz	2.48	3.79	5.81	7.10	9.04
18 GHz	3.27	4.91	7.41	8.97	11.32
23 GHz	4.70	6.94	10.31	12.39	15.49
60 GHz	13.97	18.93	25.75	29.70	35.33
80 GHz	16.09	21.40	28.55	32.64	38.41

The attenuation exceeded for other percentage of time P in the range 0.001% to 1% may be calculated using power law equation 11 [16], [19]:

$$A_p/A_{0.01} = C1 * P^{-(C2 + C3 * \log P)} \quad (11)$$

Where $C1 = (0.07^{C0}) * [0.12^{(1-C0)}]$ (11a)

$$C2 = 0.855 * C0 + 0.546 (1-C0) \quad (11b)$$

$$C3 = 0.139 * C0 + 0.043 (1-C0) \quad (11c)$$

$$C0 = 0.12 + 0.4 [\log (f/10)^{0.8}] \quad (11d) \{f \geq 10\text{GHz}\}$$

P is the percentage of time rain exceeded for path attenuation A_p that is equal to fade margin which is calculated using equation 16 in below paragraphs.

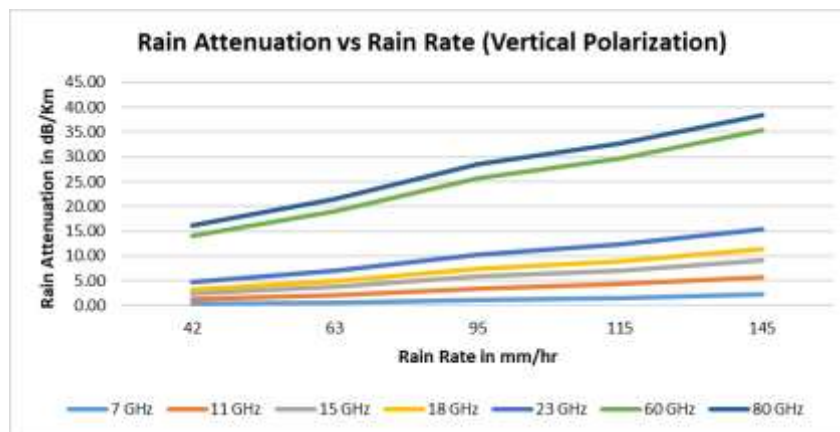


FIGURE 5: Rain Rate vs Rain Attenuation in dB/Km for Vertical Polarization

TABLE 7: Attenuation in dB/Km for Horizontal Polarization

Horizontal Polarization					
Frequency	Rain Rate (mm/hr)				
	42	63	95	115	145
7 GHz	0.49	0.89	1.63	2.16	3.04
11 GHz	1.66	2.71	4.46	5.63	7.45
15 GHz	2.98	4.71	7.46	9.25	12.00
18 GHz	4.04	6.26	9.76	12.00	15.42
23 GHz	5.85	8.85	13.47	16.37	20.74
60 GHz	15.05	20.53	28.12	32.54	38.86
80 GHz	16.72	22.31	29.89	34.24	40.38

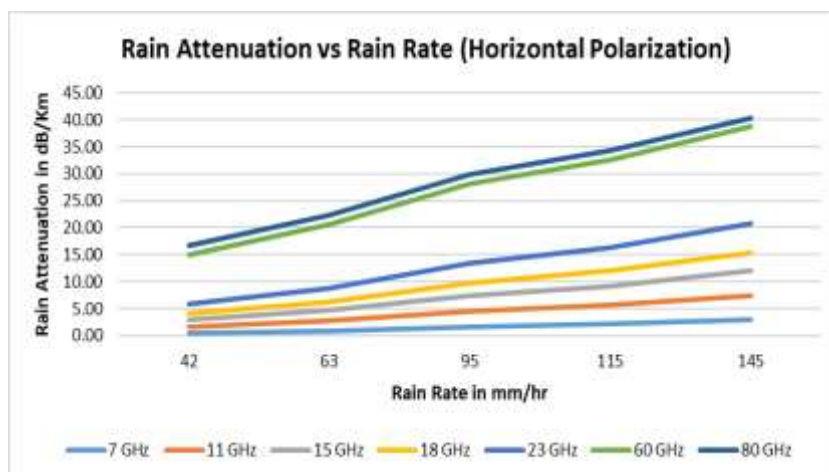


FIGURE 6: Rain Rate vs Rain Attenuation in dB/Km for Horizontal Polarization

From the tables 6 and 7, it is evident that rain attenuation is lesser for vertical polarization than horizontal polarization. The field study also confirms that vertically-polarized radio links perform better than horizontally-polarized links (or waves) [41]. Therefore, vertical polarization is preferred for designing and installing a mmW link. Rain attenuation is significantly higher at E and V band frequencies which is to the tune of 12 to 20 dB with reference to traditional bands. A practical study of a 3-Km long link of E-band conducted in East China which confirms that E-band radio waves are highly sensitive to light rainfall [45]. This reduces the reliability or availability of longer links planned in E band and recommended to limit the use shorter hop length up to 3 Km maximum [37]. One more factor known as Wet Antenna Attenuation (WAA) is caused by a water layer forming on antenna radomes during rainfall events or dew occurrence which can cause attenuation to E-band waves. The antenna covered with radome experienced WAA of approximately 2 dB which can be further decreased to 0.3 dB when a radome with hydrophobic coating is used [48].

➤ **Attenuation due to Atmospheric gases and Precipitation:** When radio signals travel through the atmosphere, these are absorbed by the molecules of oxygen, water vapours and other gases present in the atmosphere and result in transmission losses. These losses are greater on certain frequencies, coinciding with the mechanical resonant frequencies of gas molecules. According to ITU-R P.676-13 recommendations, attenuation due to oxygen and water vapour is highest to the tune of about 15 dB/km around 60 GHz i.e. V-band frequencies [6], [7]. This attenuation is over and above the FSPL and rain attenuation. **Due to these additional losses, V band becomes less useful for longer hops.** Its use is restricted to a few hundred meters but less than 1 Km or V band is mostly deployed for indoor applications. At E-band frequencies, these losses are less than 1 dB. A study conducted on 12.2 Km long link over sea confirms that the amount of water vapor in the atmosphere affects signal power attenuation. Higher the absolute humidity, lower the received signal

power. In a short time of 30 seconds, the received power variation can be as high as 10 dB [41]. Therefore, E-band is more suitable for telecommunication networks and is preferred by service providers.

➤ **Attenuation due to diffraction and multipath fading:** Point to point links are established based on the clear line-of-sight (LOS) available between two points. For long hops with water path or plain surface, the signal can reach to the receiver directly and also through reflection but with phase difference which can cause degradation in received signal causing fading effect. In case of no clear LOS, the signal can still reach to the receiver via reflections from other objects like buildings, water bodies, or plain surfaces in the close proximity to the receiver or via diffraction or wave bending [30], [31]. The link performance is impacted significantly by diffraction and multipath fading. But due to very small wavelength, there are rare chances of reflection and diffraction losses for mmW signals. Hence, attenuation due to diffraction and reflection are considered zero while doing the link budget planning in E and V- bands [38]. An experimental study of E-band transmission over long haul shows no strong multipath and channel depolarization is found relatively low [42].

➤ **Receiver Threshold for BER of 1E-6:** Receiver threshold is another name of receiver sensitivity. It is defined as the minimum signal at an acceptable bit error rate (BER) of 1E-6. It depends on RF bandwidth, carrier to noise ratio (C/N), and Noise Figure of radio. According to ITU-R F.1101 recommendations, the receiver threshold can be calculated using equation 12 [17], [14], [39], [93].

$$\text{Receiver Threshold} = C/N + NF + 10 \log B + kT + \text{FEC Imp. Factor} \quad (12)$$

Where C/N is Carrier to noise ratio and can be calculated using equation 13.

$$C/N = 10 \log (E_b/N_0) + 10 \log (F_b/B) \quad (13)$$

NB = Noise Figure = 1 dB (Typical)

kT-Boltzman's constant = -174.1 dBm/273°K

Fb = Data Rate in bps (bits per second)

FEC Imp. Factor = -3.5 dBm

Fb/B is equivalent to the theoretical value of spectral efficiency (SE) which is nothing but the number of bits per symbol as given in Table 7. Hence, the C/N equation can be re-written as equation 14:

$$C/N = E_b/N_0 + 10 \log (SE) \quad (14)$$

Where SE = Spectral Efficiency = Fb/B

Practically, only 75% Spectral efficiency can be achieved as calculated in table 7. Eb/No values are considered as given in ITU-R F.1101 recommendations. The receiver threshold is calculated for various modulation levels using equations 12, 13 and 14 and given in table 8 [29].

TABLE 8: Eb/No, C/N, S/N and Receiver Threshold

Modulation	Eb/No (dB)	No. of bits / Symbol	Spectral Efficiency (Practical)	S/N (dB)	C/N (dB)	Threshold (dBm)
QPSK / 4-QAM	10.5	2	1.5	13.5	12.3	-80.4
8-PSK	14.0	3	2.3	18.8	17.5	-75.1
16-QAM	17.0	4	3.0	20.5	21.8	-70.8
32-QAM	18.9	5	3.8	23.5	24.6	-68.0
64-QAM	22.5	6	4.5	26.5	29.0	-63.6
128-QAM	24.3	7	5.3	29.5	31.5	-61.1
256-QAM	27.8	8	6.0	32.6	35.6	-57.0
512-QAM	28.9	9	6.8	35.5	37.2	-55.4

Adaptive Coding and Modulation (ACM): Modulation level and coding schemes shifts from higher to lower mode when link performance degrades due to rain fading or interference to ensure that the link is operational satisfactorily but at a lower modulation level to provide reduced throughput. Different throughput and availability targets are defined for different ACM levels which is more relevant and significant rather than defining the availability and throughput targets at highest modulation level [28], [32]-[35].

➤ **Receiver Signal Strength (RSS):** The signal received at receiver is called RSS. The formula to calculate RSS is given in below equation 15 [22], [29].

$$\text{RSS (dBm)} = \text{Tx PWR} + \text{GT} - \text{FSPL} - \text{EL} + \text{GR} - \text{WL} - \text{M} \quad (15)$$

Where Tx PWR = Transmit Power in dBm

GT = Transmit Antenna Gain in dBi

FSPL = Free Space Path Loss in dB

EL = Other Environmental losses in dB

GR = Receive Antenna Gain in dBi

WL = Waveguide losses in dB which is 0 dB in case of slip-fit antenna with radio

M = Field margin in dB which is normally considered 1 to 3 dB

Field margin is considered as 1 to 3dB which normally occurs due to an error in antenna alignment. Other environmental losses are taken as explained under sections III previously.

➤ **Fade Margin:** FM (Fade Margin) is the difference between RSS and receiver threshold and can be computed by equation 16 [14], [21], [22].

$$FM (dB) = RSS - \text{Receiver Threshold} \tag{16}$$

➤ **Link Outage Probability and Reliability:** The reliability of a mmW point to point radio link may be calculated using the formula suggested by GTE Lenkurt Incorporated [20], Robert G. Winch [14] and other references [21], [29] as written in below equations 17 - 22.

$$\text{Outage Probability of an unprotected system} = P_F = a \cdot b \cdot 6 \cdot 10^{-7} \cdot f \cdot d^3 \cdot 10^{-F/10} \tag{17}$$

- Where
- a = Terrain factor (refer to Table 9)
 - b = Climate factor (refer to Table 9)
 - f = Frequency in GHz
 - d = Path Length in Km
 - F = Fade margin in dB

The percentage reliability of a link may be calculated using below the equation 18.

$$\% \text{ Reliability} = 100 \cdot (1 - P_F) \tag{18}$$

TABLE 9: Terrain Factor and Climate Factor

Type	Terrain Factor	Climate Factor
	a	b
Smooth / Coastal / Humid	4	0.5
Average / Some Rough	1	0.25
Rough / Dry / Mountain	0.25	0.125

Equation 17 gives the reliability of one-way communication. Since the link is full duplex, the both-way reliability is calculated by simply multiplying the result of equation 18 by two. Accordingly, the outage duration of a link in a year can be easily calculated by applying equations 19 and 20.

$$\text{Outage duration in a year (one way)} = 365 \cdot 24 \cdot 60 \cdot 60 \cdot P_F \text{ seconds} \tag{19}$$

$$\text{Outage duration in a year (both ways)} = 2 \cdot 365 \cdot 24 \cdot 60 \cdot 60 \cdot P_F \text{ seconds} \tag{20}$$

Outage probability due to rains is calculated using equations 5-11. Therefore, total outages are calculated by adding both i.e. due to rains using equation 5-11 and normal flat fading using equation 20. Accordingly, the reliability of a link may be computed using equations 21 and 22.

$$\text{Total Outage (Seconds)} = \text{Outage due to Rains} + \text{Outage due to Fading} \tag{21}$$

$$\% \text{ Reliability of a link} = 100 \cdot (\text{total seconds in a year} - \text{Total Outage}) / \text{total seconds in a year} \tag{22}$$

Reliability gives the total uptime or availability of a link during the observation period of link performance. Table 9 gives an idea and becomes handy to estimate outage durations in a year, month and day for various reliability requirements. Industry wide, 99.5% and 99.9% are acceptable reliability values for based on the criticality of the traffic running on the links in the network. For voice and most critical applications, 99.95% and 99.99% reliability is considered while planning.

TABLE 10: Reliability Vs Outage in Minutes

Reliability	Outage	Outage in Minutes		
		in a Year	in a month	in a day
99.999%	0.001%	5.256	0.438	0.0146
99.995%	0.005%	26.28	2.19	0.073
99.99%	0.01%	52.56	4.38	0.146
99.95%	0.05%	262.8	21.9	0.73
99.9%	0.1%	525.6	43.8	1.46
99.5%	0.5%	2628	219	7.3
99%	1.0%	5256	438	14.6
98%	2.0%	10512	876	29.2
97%	3.0%	15768	1314	43.8
96%	4.0%	21024	1752	58.4
95%	5.0%	26280	2190	73

➤ **Channel Bandwidth vs Throughput vs Modulation:** For E-band, RF channel bandwidth is 250 MHz. Multiple channels can be clubbed to get more data throughput [3], [8]. A simple process to calculate data throughput for a given channel bandwidth is demonstrated in this section. This is based on practical experience and standard formulas given in various technical literature and ITU-R recommendations. Data throughput depends on the spectral efficiency of a modulation as given in equation 24. The number of bits of data accommodated in one hertz of RF bandwidth gives us spectrum efficiency as given in equation 23 [29].

$$\text{Theoretical Formula: Spectral Efficiency } (\eta) = \text{Log}_2 (M) \quad (23a)$$

$$\text{Where } M = \text{Level of modulation (no. of symbols)}$$

$$\text{Practical Formula: Spectral Efficiency } (\eta) = 0.75 * \text{Log}_2 (M) \quad (23b)$$

$$\text{Data Throughput or Capacity (Mbps)} = \eta * \text{RF Bandwidth in MHz} \quad (24)$$

In the case of BPSK modulation, one bit is used that gives two symbols. Ideally, one bit per second should be accommodated in one hertz of RF bandwidth which gives spectral efficiency of 1 as per equation 23a. Since the data bits are square wave and filters are rounded (unlike the sharp frequency cut-offs associated with square wave), only around 75% efficiency is achieved which corresponds to accommodating only 0.75 bits/sec per hertz of RF bandwidth. So, the practically achievable spectral efficiency for BPSK modulation system is only 0.75. Similarly, for QPSK modulation, it is 1.5. We can calculate spectral efficiencies for higher modulation systems accordingly. Hence equation 23b is used for calculating the data throughputs of a system. Table 10 gives data throughput calculations for various modulation types starting from BPSK to 4096-QAM.

TABLE 11: Modulation, Spectral Efficiency and Data Throughput for E-Band Radio

RF Channel BW (MHz)	Modulation	No. of Bits /Symbol	M	Theoretical Spectral Efficiency (bps/Hz)	Practical Spectral Efficiency (bps/Hz)	Channel Capacity (Mbps)	Capacity Increase %
250	BPSK	1	2	1	0.75	188	
	QPSK	2	4	2	1.50	375	100%
	8-PSK	3	8	3	2.25	563	50%
	16-QAM	4	16	4	3.00	750	33%
	32-QAM	5	32	5	3.75	938	25%
	64-QAM	6	64	6	4.50	1125	20%
	128-QAM	7	128	7	5.25	1313	17%
	256-QAM	8	256	8	6.00	1500	14%
	512-QAM	9	512	9	6.75	1688	13%
	1024-QAM	10	1024	10	7.50	1875	11%
	2048-QAM	11	2048	11	8.25	2063	10%
	4096-QAM	12	4096	12	9.00	2250	9%

An increase in modulation level increases the throughput significantly as we move from BPSK to QPSK to 256-QAM to 4096-QAM. But with the increase in modulation level, demodulation complexities are increased and degrades receiver threshold by approximately 3dB for every next level of modulation. After certain modulation level, the penalties are much more than the gain of throughput as is evident from table 10 that capacity increase is around 11% or less for modulation beyond 512-QAM. In addition, there is a reduction of 1 to 2 dB transmit power reduction at higher modulations due to higher linearity requirements as well. Therefore, most of the E-band radio manufacturers have restricted the modulation use upto 256-QAM. However, link planners can opt higher modulation levels if the links are really for very short distances or meets specific link planning capacity and reliability objectives.

Now, there is further possibility to increase the data throughput by combining multiple RF channels. Table 12 gives the estimated data throughput when two to eight channels are combined. 12 Gbps throughput for 256-QAM and 18Gbps for 4096-QAM modulation can be achieved when eight RF channels are combined which are as good as fiber capacities [37]. However, a combining of channels add more losses due to splitters and combiners which impacts on the hop lengths. The combining losses are approximately 3 dB to 20 dB when two or more channels are added using a normal diplexers. The combining losses can be minimized to max 1.7 dB per channel by using multiplexers designed based on Turnstile Junction technology [47]. Accordingly, the XPIC configuration can also be implemented which doubles the capacity without additional combiner losses.

Bands and Carrier Aggregation (BCA): As noted in previous sections, the rain attenuation and FSPL in E and V band frequencies are greater than the traditional microwave bands. As a result, hop distances are very small (max 3 km in E band) which further reduces in higher rain intensity regions. In order to improve the physical hop length, there is a smart concept to combine or aggregate multiple frequency channels in different frequency bands (for example E band and 15GHz Band). The different performance targets for capacities and availability are defined differently for different frequency bands [32], [33].

TABLE 12: Data Throughput when multiple channels are combined

Modulation	Aggregate Capacity (Mbps) of Multiple RF Channels					
	1* 250 MHz	2* 250 MHz	3*250 MHz	4*250 MHz	6*250 MHz	8*250 MHz
BPSK	188	375	563	750	1125	1500
QPSK	375	750	1125	1500	2250	3000
8-PSK	563	1125	1688	2250	3375	4500
16-QAM	750	1500	2250	3000	4500	6000
32-QAM	938	1875	2813	3750	5625	7500
64-QAM	1125	2250	3375	4500	6750	9000
128-QAM	1313	2625	3938	5250	7875	10500
256-QAM	1500	3000	4500	6000	9000	12000
512-QAM	1688	3375	5063	6750	10125	13500
1024-QAM	1875	3750	5625	7500	11250	15000
2048-QAM	2063	4125	6188	8250	12375	16500
4096-QAM	2250	4500	6750	9000	13500	18000

➤ **LOS and Path Clearance:** To plan a mmW link between two points, the clear line of sight must be ensured. Antenna heights are planned to confirm that the sum of the earth bulge, any building or tree or hill feature or any other obstruction height and first Fresnel Zone radius are cleared. As noted from Table 4, the HPBW at E and V band frequencies is very small like a narrow pencil beam, there is no chance of reflection.

The first Fresnel Zone radius can be calculated using the formula given at in equation 25 [14], [22].

$$\text{First Fresnel Zone Radius} = F1 = 17.31 * \{D/(4*f)\}^{1/2} \quad (25)$$

Where D = Hop Length in Km; f = Frequency in GHz

Accordingly, F1 calculated for 1 to 5 Km hop length for E, V and traditional bands are presented in Table 13.

TABLE 13: First Fresnel Zone Radius

Hop Length (Km)	Fresnel Zone F1 in meter		
	E-Band	V-Band	Traditional Band
	80 GHz	60 GHz	15 GHz
1	0.97	1.12	2.23
3	1.68	1.94	3.87
5	2.16	2.50	5.00

The First Fresnel zone radius is very small i.e. less than 2 meters for 3 km hop length. Earth bulge is also very small for 1 to 3 or even 5 km long links. If a clear line-of-sight is established just by observing the far end site from the local site, then a link can be easily established between the two points because of the small Fresnel zone radius and negligible earth bulge height.

KEY PERFORMANCE INDICATORS (KPI) AND MATRIX

The key performance parameters of mmW links are [23], [29], [40]:

- Data Capacity or Throughput or Committed Information Rate (CIR)
- Reliability of a link

As discussed in the previous sections so far, the following parameters influence both key parameters, i.e. throughput and reliability:

- Higher modulation level gives higher throughput. Refer to Table 10.
- But higher level modulation degrades the receiver threshold. Refer to Table 7.
- Since the receiver threshold decreases with the increase of modulation level, the fade margin of the link degrades by the same amount and ultimately reduces link reliability and increases outage duration.
- To improve the reliability of a link, the following measures should be considered –
 - Increase transmit power within the permissible limit of EIRP as per ITU-R recommendations.
 - Increase transmit and receive antenna sizes within the permissible limit of maximum EIRP. Doubling the antenna size at both transmitter and receiver end gives a gain of 12 dB in fade margin which significantly improves the link reliability.
 - Hop length is another factor which impacts the link reliability. Doubling the hop length increases FSPL by 6 dB and significantly impacts reliability and throughput. This additional path loss can be mitigated either by increasing the transmit power or increasing the antenna size at the transmitter, receiver, or both locations. Refer to Table 4 and 5.
 - Rain attenuation is another important parameter that impacts reliability to a great extent during heavy rain fall. Links in mmW work very satisfactorily in medium rainfall regions where it is around 25-30 mm/hr. But in extreme rainfall

regions where rain intensity is more than 42mm/hr, the reliability of the mmW links suffers immensely. Refer to Table 5 and 6 and Figures 5 and 6 for rain attenuations.

A matrix of key parameters i.e. throughput and reliability with respect to various modulation levels is proposed for analysis purposes. This matrix also captures the effect of antenna size. Although the link availability targets are kept 4 to 5 nines (means 99.99% to 99.999%) for a minimum committed information rate (CIR) or throughput. But for a maximum throughput, a less conservative target such as 2, 3, or 4 nines are set by network operators without any strong reasoning [23], [37].

Backhaul Traffic Availability (BTA): ETSI introduced a new KPI for microwave planning [43], [28]. To define in simple terms, BTA is the targets defined differently for each ACM level based on the committed throughput. The peak rate is demanded by the RAN with a small probability. And committed rates for RAN sites survivability and very high value traffic is much lesser than the peak traffic rate. Therefore, the BTA targets can be pushed up to 99.5% - 99.9% with negligible impact on end user quality of experience [43], [50]. The throughput for various modulations are demonstrated in below tables 14 to 17 for better understanding.

SAMPLE LINK BUDGET AND FIELD PERFORMANCE

Refer to table 14 for 0.93 Km hop length, table 15 for 1.8Km long link, table 16 for 3.06 km link, and table 17 for 4.76 Km hop length for key performance indicators and matrix [29].

TABLE 14: Performance Matrix for 0.93 Km long hop

Hop Distance (Km)	0.93						
Frequency (GHz)	80						
Transmit Power (dBm)	20						
RF Bandwidth (MHz)	250						
Polarization	Vertical						
Rain Rate (mm/hr)	42						
Rain Attenuation (dB)	14.26						
Tx & Rx Antenna Size (m)	0.3	0.6					
Tx & Rx Antenna Gain (dBi)	45	51					
RSS (dBm)	-20.08	-8.04					
Performance Matrix							
Modulation	QPSK	8-PSK	16 QAM	32-QAM	64-QAM	128-QAM	256-QAM
Throughput (Mbps)	375	563	750	938	1125	1313	1500
% Reliability with 0.3m Antenna	99.994	99.991	99.987	99.983	99.974	99.967	99.949
% Reliability with 0.6m Antenna	99.998	99.997	99.996	99.994	99.992	99.989	99.984

The reliability of 0.93 Km long hop is very good and above the design target of 99.5% with 0.3 m antenna itself. Hence, planning this link with 0.6 m antenna is not required. As a result, this link is designed with 0.3 m antenna only and meets the reliability requirements. Also it is worth noting that RSS associated with 0.6 m antenna is -8.04 dBm which is very high and falls in the saturation region potentially damaging the receiver front end low noise amplifier (LNA). It should be ensured to have RSS less than -15.00 dBm typically which falls under the linear region and the safe range for LNA operations.

TABLE 15: Performance Matrix for 1.8 Km long hop

Hop Distance (Km)	1.8						
Frequency (GHz)	80						
Transmit Power (dBm)	20						
RF Bandwidth (MHz)	250						
Polarization	Vertical						
Rain Rate (mm/hr)	42						
Rain Attenuation (dB)	26.42						
Tx & Rx Antenna Size (m)	0.3	0.6					
Tx & Rx Antenna Gain (dBi)	45	51					
RSS (dBm)	-25.82	-13.78					
Performance Matrix							
Modulation	QPSK	8-PSK	16 QAM	32-QAM	64-QAM	128-QAM	256-QAM
Throughput (Mbps)	375	563	750	938	1125	1313	1500
% Reliability with 0.3m Antenna	99.885	99.839	99.785	99.737	99.632	99.55	99.36
% Reliability with 0.6m Antenna	99.944	99.924	99.902	99.883	99.845	99.871	99.756

For a 1.8 m long hop, we are able to achieve the reliability objectives with 0.3 m antenna up to 128-QAM. Hence, there is no need to use 0.6 m antenna. In the low rain intensity regions, 0.3 m antenna is sufficient to provide desired reliability at 256-QAM as well. Alternatively, it is better to choose 3 dB more transmit power that can improve the performance rather than going for higher size antenna of 0.6 m

TABLE 16: Performance Matrix for 3.06 Km long hop

Hop Distance (Km)	3.06	
Frequency (GHz)	80	
Transmit Power (dBm)	20	
RF Bandwidth (MHz)	250	
Polarization	Vertical	
Rain Rate (mm/hr)	42	
Rain Attenuation (dB)	42.3	
Tx & Rx Antenna Size (m)	0.3	0.6
Tx & Rx Antenna Gain (dBi)	45	51
RSS (dBm)	-30.43	-18.39

Performance Matrix

Modulation	QPSK	8-PSK	16 QAM	32-QAM	64-QAM	128-QAM	256-QAM
Throughput (Mbps)	375	563	750	938	1125	1313	1500
% Reliability with 0.3m Antenna	99.358	99.13	98.859	98.623	98.108	97.699	96.739
% Reliability with 0.6m Antenna	99.657	99.555	99.442	99.348	99.158	99.018	98.718

For 3.06 Km hop, it is evident that even 0.6m antenna is unable to deliver the desired reliability of 99.5%. Hence, higher transmit power versions are to be used to achieve the target value. Even if the rain intensity in a region is less than 42 mm/hr, the reliability objectives can be met without increasing the transmit power.

TABLE 17: Performance Matrix for 4.76 Km long hop

Hop Distance (Km)	4.76	
Frequency (GHz)	80	
Transmit Power (dBm)	20	
RF Bandwidth (MHz)	250	
Polarization	Vertical	
Rain Rate (mm/hr)	42	
Rain Attenuation (dB)	61.03	
Tx & Rx Antenna Size (m)	0.3	0.6
Tx & Rx Antenna Gain (dBi)	45	51
RSS (dBm)	-34.26	-22.22

Performance Matrix

Modulation	QPSK	8-PSK	16 QAM	32-QAM	64-QAM	128-QAM	256-QAM
Throughput (Mbps)	375	563	750	938	1125	1313	1500
% Reliability with 0.3m Antenna	97.914	97.199	96.343	95.59	93.919	92.572	89.311
% Reliability with 0.6m Antenna	98.85	98.532	98.177	97.884	97.287	96.846	95.892

For 4.76 Km long hop, the reliability objectives are not even met with 0.6 m antenna. Even after increasing transmit power, it may be difficult to achieve the desired reliability of 99.5% at 256-QAM. Hence, such long hops should not be planned. In the regions where rainfall intensity is much lower and in the range of 25 mm/hr, the reliability may be achieved even for 5 Km links.

Accordingly, following points can be concluded from the above sample link's KPI matrix:

- Links around 1 Km and below are good even with smaller antenna i.e. 0.3 m or 0.2 m and with lower transmit power than +20 dBm.
- Link planning beyond 3 Km should be avoided if the rain fall rate in the region is 42 mm/hr or more. If the rainfall in the region is very less, then, higher hop lengths beyond 3 Km can be planned.
- For regions where rain fall is higher than 42 mm/hr, the hop length will be further reduced and may be restricted to 1.5 or 2 Km only.

Field Performance and Observations:

Field testing was done in Hungary where ITU rain-zone "K" of rain fall intensity (with 0.01% of time) equal to 42mm/h on three hop lengths (i.e. 500m, 850m and 1 Km) to provide throughput of 9.3 Gb/s. The link availability measured was approximately 99.95% or better [87] which is quite good as per industry standards.

Three E-band radio links having clear line-of-sight (LOS) with 1 GHz channel bandwidth were tested over long distances around 12 Km in different environments i.e. across lake, desert, and sea. Following points are noted on the performances of these links in terms of pathloss, fading, polarization, multipath effects except rain fade which was not covered under the testing [88], [89]:

- E-band long distance propagation is greatly affected by particular environments and meteorological conditions. The additional attenuation varies from 0.15 to 0.7 dB/Km which increases with air humidity.
- Vertical polarization performed better by 4-7 dB compared with Horizontal polarization.
- Severe short term fading up to -25, -12, and -4 dB is observed caused by the effects of atmospheric turbulences along the propagation paths.
- ITU-R P.676 model fails to predict E-band pathloss in several conditions i.e. under-estimates pathloss for horizontally polarized waves in dry and thin air while over-estimates vertically polarized wave in humid air at sea level.
- The long-range channels to some extent deflect wave polarization. However, relatively high XPR in the measurements indicate great potential of polarized MIMO in backhaul transmission to double the data rates.
- No significant multipath has been observed.

A 2.9 Km long E-band backhaul radio link was installed on the roof of Ericsson building in Sweden and tested. The measurements were carried out from 7th -17th June 2017. The receive signal level and path attenuation was measured in difference weather conditions. It was noted that the measured attenuation is greater than the theoretical signal attenuation by 4-4.5 dB mainly due to humidity and wet antenna [90].

In another study, a 52- Km long E-band LOS link was installed and studied. 3.6 Gb/s data rates are achieved with 64QAM modulation. The results point out that E-band propagations in long distances are greatly affected by atmospheric turbulences, even if there is no rain. No strong multipath is observed which favors polarization multiplexing [91].

E-Band performance for backhauling was evaluated in urban city in two scenarios i.e. on-ground pole mounted backhauling and rooftop outdoor-to-indoor (O2I) for a hop length of approximately 700m. The results show that E-band link on ground is greatly affected by multipath effects. To avoid this severe fading, the antennas must be installed at sufficient height on-ground pole. In rooftop O2I link, the signal quality is quite stable but around 4dB additional penetration loss due to glass window is observed [92], [95].

One more field study in Budapest Hungary shows that E-band links are severally impacted by the rains but hardly affected by fog [94].

Maximum power path loss models for indoor environments at 83.5 GHz (E-band) tested and found that E-band radios steer their pencil-beam antenna towards the direction of arrival that has maximum power in accordance with path-loss model. Additionally, it was also accomplished that non-Line-of-sight (NLOS), the direct path was un detected due to high penetration loss; while diffracted paths were detected and their power was recorded 11-23 dB weaker than reflected path [96].

10 link (TL1 to TL10) of E-band monitored in New Delhi India in a Telco network and performance was observed on 24th April 2025 and presented in below table -18. Delhi comes under Rain region K (Rain intensity = 42 mm/hr for 0.01 % of time).

Table – 18: Field performance of 10 E-Band Links in New Delhi India

Test Link	Link Distance (Km)	TxLev e/IV	Min Mod	Max Mod	Modulation Change	Planned RSL	Max of RxLevelIV	Min of RxLevelIV	MAX RSL Range	ES	SES	UAS	Availability
TL 1	0.88	9	QAM-1024	QAM-1024	No	-22.36	-21.3	-23.1	<3 dB	0	0	0	100
TL 2	1	10	QAM-1024	QAM-1024	No	-22.5	-20.9	-24.1	within 4 dB	0	0	0	100
TL 3	1	10	QAM-1024	QAM-1024	No	-22.52	-20.7	-28	<8 dB	0	0	0	100
TL 4	1	10	QAM-1024	QAM-1024	No	-22.5	-22.2	-26.6	<6 dB	0	0	0	100
TL 5	2	13	QAM-512	QAM-512	No	-25.93	-22.7	-27.9	<6 dB	0	0	0	100
TL 6	2	13	QAM-512	QAM-512	No	-25.95	-24.6	-33.9	<10 dB	0	0	0	100
TL 7	2.98	15	QAM-64	QAM-64	No	-27.82	-24.9	-49	<25 dB	0	0	0	100
TL 8	3.51	15	QAM-256	QAM-256	No	-29.44	-29.6	-43.6	<15 dB	0	0	0	100
TL 9	4.93	16	QAM-64	QAM-64	No	-35	-33.1	-76.4	<45 dB	13	4	0	100
TL 10	5.06	16	QAM-32	QAM-128	Yes	-32.27	-48.8	-61.3	<15 dB	13	12	0	100

0.6m high performance antenna were used. Hop-distances of tested links are varying from 0.9 Km to 5 Km. From above table, following observations are made:

- Path attenuation was in line with the link budget model as presented in this review paper. The variation between planned RSL and actual RSL is within few dB i.e. < 2dB.
- RSL variation is within acceptable limits for links up 3 Km (TL 1 – TL 8). There is no change of modulation and link remain stable during the observation period.
- Links around 5 KM (TL 9 & TL 10), suffered by severe RSL degradation up to 45 dB due to rains and caused TL10 to reduce modulation from QAM 128 to QAM 32. But TL9 remained unaffected because it was designed to operate at lower modulation of QAM64.
- All links availability was 100% because there were no un-available seconds (UAS) observed during the observation period.
- The link and power budget methodology presented in this paper is certified by the field observations and found inline.

CHALLENGES IN DEPLOYMENT

It is imperative to know the limitations and challenges of E and V band technology while planning the deployment in a telecommunication network. In the previous sections, the key parameters and dependencies on various factors to get the target performance have been noted. There are some parameters which can be played with to fine-tune the desired performance, i.e. antenna size, transmit power, antenna polarization and even the modulation level. But there are some parameters which are beyond our control and depend on the environment such as rain intensity. The summary of all the challenges observed so far during the study are given below:

- An experimental study of E-Band transmission performance over 52-Kilometer terrestrial link was performed. The result of the study shows that the atmospheric conditions along the long-distance line-of-sight path greatly affect E-band propagation. Atmospheric turbulence may cause severe signal fading, even when there is no rain [42] [91]. Hence, E-band radio links are not suitable for long-haul transmission.
- Rain attenuation becomes a major issue because it drastically impacts the hop distance to achieve the desired performance of the mmW link. E-band radios are normally used up to 3 Km of hop lengths [51]. The hop distance may get extended to 5 Km in the regions that experience very low rainfalls.

- V-band mmW links are limited to be used only for very small distances i.e. only a few hundred meters due to additional attenuation of 15 dB/km at frequencies around 60 GHz. V-band is used for indoor application as well.
- Since HPBW is very narrow, i.e. < 0.5 deg, it causes difficulty for antenna alignment and also requires a very rugged and specialized mounting structure or side strut to ensure the antenna alignment is intact during the heavy wind pressures. Most of the OEMs provide an antenna alignment tool built-in within the radio to help field engineers while doing the antenna alignment.
- Towers and Masts with sway of 0.5 degree are not suitable to install these E/V band radios because of very narrow HPBW.
- Otherwise, there are chances the antenna may get misaligned even with low to moderate wind velocity. Also, antenna sizes more than 0.6 m are rarely used due to this challenge. However a special antenna that can continuously adapt and mitigate the effects of the sway by analysing the signal level received by the link and using gyroscope and accelerometer sensors to detect sway and compensating accordingly ensuring the link remains functional [50].
- E-band provides four times higher capacities than V-band.
- Because of high density of last mile links in densely urban areas, the interference issues are frequently observed. To mitigate interferences, a careful installation of radios can practically eliminate the interfering signals blocked by building edges walls [97].

Novel network planning process for E-Band: Based on above analysis, a novel and simple planning process for E-band networks is proposed in below table 19. The link and network planning process using traditional frequency band and E-band is demonstrated.

It is to be noted that the planning process with traditional frequency band is very much complex and time consuming. Major time consuming activities i.e. physical route survey, reflection & multipath, and network interference analysis are not required when designing a link of E-band.

Table 19: Planning Steps– E- Band Vs Traditional Band

Traditional Frequency Bands		E-Band	
Steps	Activity	Steps	Activity
1	Capacity and Specification Requirement	1	Capacity and Specification Requirement
2	Nominal Network Planning on the Map	2	Visual LOS verification from site to site (no route survey required).
3	LOS Verification by route survey		
4	Path Profiling	3	Antenna height is simply defined based on visual LOS verification. (No other analysis required because of very narrow pencil beam-width)
5	Fresnel zone clearance & Antenna Height Calculation		
6	Reflection & Multipath analysis		
7	Link Budget Analysis	4	Link Budget Analysis
8	Frequency Planning	5	Simple frequency planning (Interference analysis not required because path loss is high).
9	Frequency Interference analysis		
10	Design document release for deployment	6	Design document release for deployment

GAPS IN PRESENT TEHNOLOGY

E-band radio and antenna designs are based on traditional method. Meta material based antenna designs need to be explored which provides better isolation and are light in weight and ultimately reduces the costs. Few areas for further research and development in E-band technologies are proposed to explore:

- Design the feed of a parabolic antenna using metamaterial instead of waveguide. This can reduce the over all weight and cost of the antenna.
- Explore additional polarization techniques like angle polarization in addition to horizontal and vertical polarization to enhance the overall data capacity transmission across a single link.
- By using angle polarization as 3rd and 4th type of polarization, the additional losses due to combiners and splitters for multiple RF channels can be eliminated and results in enhancing the hop distance or reduces transmit power requirements.

Conclusion

From the detailed review of E and V-band mmW technology, it is evident that fiber networks like with high capacities can be delivered wirelessly by using E-band especially. Where fiber reachability is a challenge, E-band is the solution to bridge the gap wirelessly for back-hauling or front-hauling as required. mmW links can be implemented very quickly and at much lower cost than laying a fiber network. E-band is better than the V-band because of additional attenuation of 15 dB/Km at V-band frequencies in the atmosphere due to oxygen and water vapors. However, V-band links are still planned for medium capacities and for very short distances of a few hundred meters only. E-band links can go up to 3 Km in

moderate rain conditions while the range can be further extended to 5 Km in low rain regions. Transmitter power and antenna sizes are the two important parameters to play with when planning a hop for targeted performance in terms of throughput and reliability. Due to an antenna's very narrow HPBW, its alignment can be challenging. However, alignment tool provided by OEMs helps in eliminating these difficulties. The use of a side strut with an antenna is must to ensure the antenna is stable enough during moderate to high wind velocity scenarios. The primary application of mmW technology is in 4G and 5G telecommunication networks where service providers use it to connect a small cell BTS to core network and also to provide building-to-building connectivity across high traffic roads where fiber laying is not feasible. Its major advantages are that it is easy to plan, quickly deployed and offers a low cost of ownership. The performance of ten E-band links are also observed in field installed in a telco network in New Delhi India and verified the results according to the link budget methodology presented in this paper. Additionally, the gaps in the present research are highlighted for future research work in E-Band technology.

TABLE 18: Summary of Important Acronyms

Acronym	Meaning
mmW	Millimeter Wave
GSM	Global System of Mobile Communication
ETSI	European Telecommunications Standard Institute
ITU	International Telecommunication Union
ITU - R	International Telecommunication Union - Radio
BPSK	Binary Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
EB	Exa Byte
mm/hr	millimeter/hour
Mbps	Mega bit per second
Gbps	Giga bit per second
ROW	Right of Way
FSPL	Free Space Path Loss
HPBW	Half Power Beam Width
FM	Fade Margin
BER	Bit Error Rate
LOS	Line-of-Sight
XPIC	Cross Polarization Interference Cancellation
ATPC	Automatic Transmit Power Control
ACM	Automatic Code Modulation
RSS	Receive Signal Strength
EIRP	Effective Isotropic Radiated Power
OEM	Original Equipment Manufacturer
dB	Decibel
dBm	Decibel with reference to 1 milliwatt
dBi	Decibel with reference to isotropic antenna
ODU	Outdoor unit
RF	Radio Frequency
RAN	Radio Access Network
WAA	Wet Antenna Attenuation
GaAs	Gallium Arsenide

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ABOUT AUTHORS



Rakesh Kumar received the bachelor's degree in Electronics and Communication Engineering from Institution of Engineers, Kolkata, India in 1988, followed by MBA from Indira Gandhi National Open University, India in 1999 and M. Tech in Embedded Systems from BITS Pilani, India in 2020. He is currently perusing PhD at BITS Pilani, K.K. Birla Goa Campus, India. His research area is interference mitigation techniques in microwave antenna and radio equipment. He has 40 years of telecommunications industry experience and handled leadership roles like CTO and head of network planning, deployment & operations with specialization in microwave transmission network including fiber.



Dr. Sudeep Baudha is an Associate Professor in the Department of Electrical and Electronics Engineering at BITS Pilani, K. K. Birla Goa Campus, India. He obtained his B.E. in Electronics and Communication Engineering from Ujjain Engineering College (UEC) Ujjain in 2007, followed by an M.Tech. in Radio Frequency and Microwave Engineering from the Indian Institute of Technology (IIT) Kharagpur in 2009. He earned his Ph.D. from the Indian Institute of Information Technology Design and Manufacturing (IIITDM) Jabalpur in 2015.

Dr. Baudha's research expertise includes microstrip and planar antennas, as well as microwave communication. He has published more than 60 peer-reviewed articles in reputed international journals, conferences, and edited volumes. He has successfully completed over 10 funded research and consultancy projects supported by various government agencies and funding bodies. In addition, he has authored a book and holds two patents. He is actively engaged in the academic and research community, serving as a reviewer for several esteemed journals. He is also a member of the Institute of Electrical and Electronics Engineers (IEEE)