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FUTURE W/V-BAND SATELLITE COMMUNICATION SYSTEMS

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Final Report

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14. ABSTRACT
During this cooperative agreement, the bandwidth efficiency of a W/V-band communication channel was simulated and computed under an additive white Gaussian noise environment. These simulations incorporated measured cumulative distribution functions from the AFRL W/V-band Terrestrial Link Experiment. Simulations used the Digital Video Broadcasting-Satellite Second Generation (DVB-S2) adaptive code modulation scheme. A link margin of a W/V-band communication system was assumed. It was found that the bandwidth efficiency of the W/V-band channel was 4.27 bits/s/Hz, and the corresponding data rate was 21.37 Gbits/s per beam when the link margin was 10 dB with 5 GHz of bandwidth. Compared to the 20 Gbps peak data rates in the existing terrestrial mmWave 5G massive MIMO system at frequencies of 28 GHz and 39 GHz, improvement of the W/V-band is significant.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

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1.0 SUMMARY

A terrestrial millimeter wavelength (mmWave) 5G massive multiple-input multiple-output (MIMO) system has recently been launched at frequencies of 28 GHz and 39 GHz to deliver data at faster rate than 4G, delivering up to 20 Gigabits-per-second (Gbps) peak data rates. Since 2015, the Air Force Research Laboratory (AFRL) has measured the channel characteristics of the W and V band, and reported that the contiguous bandwidths are five times higher than those of the 5G mmWave massive MIMO system. Hence, the W/V-band can be a candidate for 6G system to meet a desirable data rate and bit error rate (BER).

The data rate is proportional to bandwidth or bandwidth efficiency (BWE) in bits/s/Hz. In this report, the BWE of a W/V-band channel is computed under an additive white Gaussian noise (AWGN) channel environment. Channel attenuation data were obtained in 2019 through another Air Force Research Laboratory (AFRL) project different from this current project. W and V band transmit (Tx) and receive (Rx) antennas were employed at 72 GHz and 84 GHz, respectively, and separated by 23.6 km in Albuquerque, New Mexico, USA. A single antenna was used for both Tx and Rx. The cumulative distribution function of the W/V-band terrestrial channel attenuation was reported and will be used in this current project.

A communication system using adaptive code modulation (ACM) has higher BWE than a fixed modulation and a fixed code rate, since the channel attenuation is time varying. For example, the 28 ACM modes in the Digital Video Broadcasting-Satellite Second Generation (DVB-S2) system will be used for this current project. A link margin of a W/V-band communication system will be assumed.

This report presents a method to compute the BWE of the W/V-band system using the available channel attenuation experiment data and 28 different ACM modes in the DVB-S2 system. Results suggest that the BWE of the W/V-band system is 4.27 bits/s/Hz and the maximum data rate is 21.37 Gbps per beam at bit-error-rate of 10^{-5} when the link margin is 10 dB and with W/V-band channel contiguous bandwidth of 5 GHz.

The 5G massive MIMO system employs multiple transmit and multiple receive antennas, e.g., 64 antennas, whereas a single transmit and a single receive antenna were used in the previous experiment, and hence was assumed in this report. If multiple transmit and receive antennas were used as the 5G massive MIMO, then the bandwidth efficiency of the W/V-band configuration will be higher. The presented method in this report can be applicable for other channel environments and other ACM modes.

2.0 INTRODUCTION

2.1 Motivation

New algorithm strategies and diverse communication techniques are constantly emerging in the telecommunications realm that consumer, commercial, government, and military users demand to push the boundaries of data throughput to receive information as quickly as possible. The AFRL has reported in 2019 that the contiguous bandwidth of a W/V-band channel can be five times larger than that of the 5G mmWave massive MIMO system [1]. It has not been studied whether a W/V-band system can show a higher data rate at desirable bit error rate (BER) than a recently launched 5G mmWave massive MIMO system. Specifically, the bandwidth efficiency has not been investigated in the literature to assess bits per second per Hz for a W/V-band system. This is the motivation of this project.

2.2 Objective

The objective of this report is to find the bandwidth efficiency (BWE) of a W/V-band channel using the measured attenuation experimental data and the ACM in the Digital Video Broadcasting-Satellite Second Generation (DVB-S2) system [3]. The contribution of this report will be to present a method of BWE computation when only a cumulative distribution function (CDF) of real measured attenuation data and an ACM scheme are available. The method and data in this report can be extended for other channels and other ACM schemes.

2.3 Literature Survey

With an interest in both terrestrial and satellite communications, recently the W/V-band channel has been studied under various weather and atmospheric conditions [1, 2]. The experiments in Albuquerque, New Mexico, USA use W/V-band satellite dish transmit (Tx) and receive (Rx) antennas using 72 GHz and 84 GHz that were separated by a distance of 23.6 km to measure the channel attenuation based on the size of rain drops (see Figure 1). These W/V-band rain attenuation measurements are used in this report to find the BWE of the W/V-band channel by applying ACM, i.e., adaptive modulation and forward error correction (FEC) codes in the ACM in the DVB-S2 system [3].

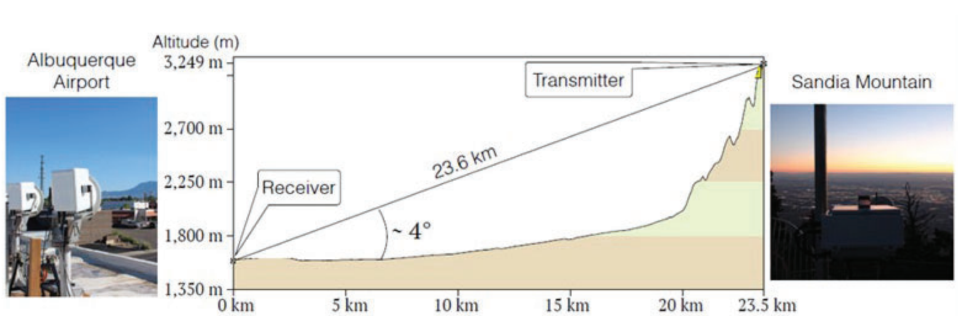

Figure 1. W/V-band Weather Attenuation Scenario

3.0 METHODS, ASSUMPTIONS AND PROCEDURES

3.1 Methods

Channel attenuation experiment data were obtained in 2019 through another AFRL project different from this current project [1, 2]. Two pairs of W/V-band satellite dish transmit and receive antennas were employed at 72 GHz and 84 GHz, respectively, and separated by 23.6 km in Albuquerque, New Mexico, USA. A single antenna was used at both transmit and receive antennas. The cumulative distribution function (CDF) of a measured W/V-band terrestrial channel attenuation was reported and will be used in this current project.

A communication system of an adaptive code modulation has a higher BWE than a fixed modulation and a fixed code rate since the channel attenuation is time varying. For example, the 28 ACM modes in the DVB-S2 system will be used for this current project [3].

A higher modulation can transmit more coded bits per modulation symbol interval T_s because $\log_2(M)$ bits/symbol are transmitted for a modulation of order M. For example, if 8-ary phase-shift keying (PSK) modulation is employed, then $M = 8$, and $\log_2(M) = 3$ bits/symbol can be transmitted. However, a higher modulation can cause a higher number of coded bit errors because symbols in the constellation plane are getting closer under an average symbol energy constraint and vice versa.

A forward error correction (FEC) using a lower code rate, R_c, i.e., a lower ratio of the number of information bits to channel coded bits, can deliver fewer information bits, but can correct more channel coded bit errors and vice versa. Hence, a lower modulation and a lower code rate will require a smaller symbol energy-to-noise ratio, E_s/N_o, to meet a certain bit-error-rate (BER) criterion, and hence, can sustain the BER quality against more severe channel attenuation, but deliver fewer information bits. Thus, the BWE in bits/s/Hz will get lower. On the other hand, a higher modulation and a higher code rate will require a higher E_s/N_o to meet the same BER and deliver more information bits. Thus, the BWE in bits/s/Hz will get higher.

Therefore, if the channel attenuation is lower, then it is desirable to use a higher modulation and a higher code rate. If the channel attenuation is higher, then a lower modulation and a lower code rate will be desirable. This ACM will achieve a higher BWE than a non-ACM by changing gears, depending on the attenuation measurement.

Figure 2 shows a graph of the portion of received power samples in decibel-milliwatts (dBm) over time in 2019. Red portions of the graph indicate where measurements were not taken due to system maintenance, while blue portions show the actual measurement values.

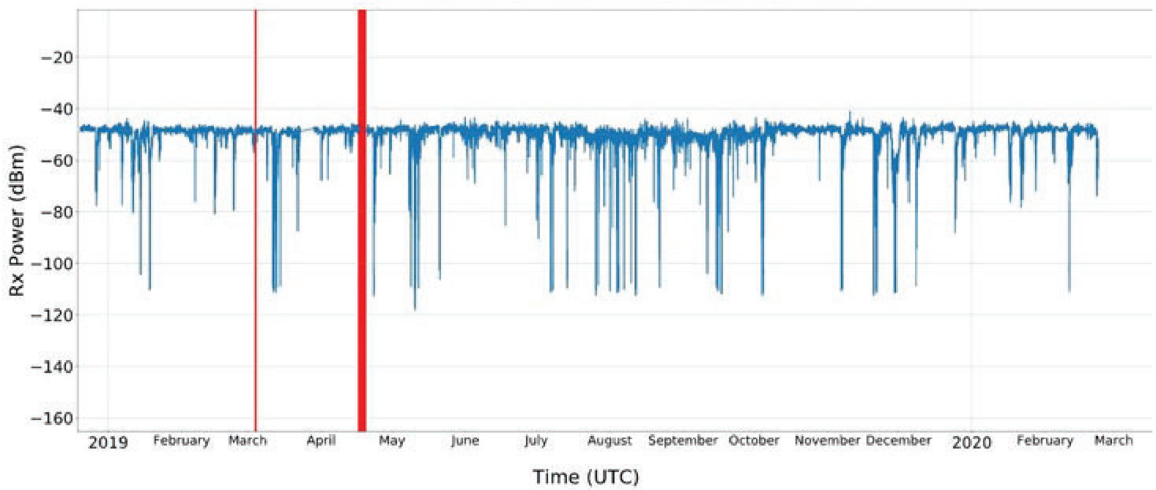

Figure 2. Measured Received Power (dBm) over Time (72 GHz, Co-polarization Channel)

The DVB-S2 satellite link has been in existence since 2014 and can select an ACM mode out of 28 possible combinations of FEC coding and modulations, depending on the channel attenuation. Table 1 lists 28 possible combinations using the Bose-Chaudhuri-Hocquenghem (BCH) code, low-density parity-check (LDPC) FEC code, and quadrature phase-shift keying (QPSK), 8PSK, 16-ary amplitude phase-shift keying (16APSK), 32-ary amplitude phase-shift keying (32APSK) modulation, as well as different code rates under the DVB-S2 model [4, 5].

Table 1. ACM and Code Rate

Adaptive Code Modulation	Code Rate (R_c)
QPSK	$\frac{1}{4}, \frac{1}{3}, \frac{2}{5}, \frac{1}{2}, \frac{3}{5}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}, \frac{5}{6}, \frac{8}{9}, \frac{9}{10}$
8PSK	$\frac{3}{5}, \frac{2}{3}, \frac{3}{4}, \frac{5}{6}, \frac{8}{9}, \frac{9}{10}$
16APSK	$\frac{2}{3}, \frac{3}{4}, \frac{4}{5}, \frac{5}{6}, \frac{8}{9}, \frac{9}{10}$
32APSK	$\frac{3}{4}, \frac{4}{5}, \frac{5}{6}, \frac{8}{9}, \frac{9}{10}$

Depending on the W/V-band channel attenuation, the best ACM mode, which is a paired modulation and an FEC, will be employed to maximize the overall bandwidth efficiency of the W/V-band channel. The BCH code is common in all combinations, and the code rate listed in Table 1 is for LDPC FEC codes. Each ACM mode has different bandwidth efficiencies (bits/s/Hz) and requires different signal-to-noise ratios (SNRs) to achieve a certain performance, e.g., 10^{-5} BER.

In general, as stated earlier, a higher ACM mode has a higher bandwidth efficiency and requires a higher SNR. A lower ACM mode has a lower bandwidth efficiency and requires a lower SNR. This is because a lower ACM mode will be more resilient against a higher attenuation than a higher ACM mode. A higher attenuation in decibels (dB) causes a proportionally lower received SNR in dB. Therefore, a lower ACM mode will be selected as the channel attenuation gets worse, i.e., higher.

Then, the exceedance probability of the measured receive power in dBm is converted into the cumulative distribution function (CDF) of the attenuation in dB for the W/V-band channel in order to find a proper ACM mode for a given attenuation in dB. The CDF provides information on the probability of the attenuation in dB. In other words, the CDF in attenuation gives the probability of the corresponding ACM mode being used for the given attenuation in dB. Each ACM mode has its own BWE (bits/s/Hz). Therefore, the overall average BWE of the W/V-band channel can be found using the CDF of the attenuation in dB.

The CDF of the attenuation is applied to compute the W/V-band link BWE by considering four different link margins in dB at which the highest bandwidth efficient ACM mode, i.e., 32APSK 9/10, can start transmission with BER $P_b \leq 10^{-5}$. In this report, E_s/N_o is used as the SNR metric. The transmitted mode is changed to an ACM with reduced E_s/N_o requirements to satisfy the $P_b \leq 10^{-5}$ threshold when the W/V-band channel attenuation worsens due to bad weather.

3.2 Assumptions

In this report, it is assumed that a set of channel attenuation measurement data for a W/V-band communication link and its corresponding cumulative probability distribution function of the attenuation are available, and that an additive white Gaussian noise or thermal noise is added to the received signal at the receiver.

The link margin in dB is the difference between the minimum expected power received at the receiver's end, and the received power at which the receiver will stop working. For example, a 10 dB link margin means that the system could tolerate an additional 10 dB of attenuation between the transmitter and the receiver. In this report, it is assumed that a link margin for the W/V-band system operation is predetermined.

Furthermore, it is assumed that a set of ACM modes, such as the 28 ACM modes in the DVB-S2 is available. Other ACM modes such as those in the Protected Tactical Waveform (PTW) can be applicable [6]. The PTW provides specifications for baseband framing, modulation, and coding, dynamic link adaptation protocols, and security features for data protection and jamming resistance.

Throughout this report, lowercase boldface letters denote column or row vectors. All italicized letters denote scalar quantities. The symbol $|x(n)|$ denotes the amplitude of a complex variable $x(n)$, and $E[X]$ stands for the expectation of a random variable, X.

3.3 Procedure

The basis of the MATLAB source code used here came from MathWorks® "DVB-S.2 Link, including LDPC Coding", which was provided online as a demonstration [7]. The MATLAB code was modified for this study to run for each ACM method (see Table 1) and various frame sizes for the input values. In the DVB-S2 system functional block diagram, there are two sources of streams: single input stream, and multiple input stream. The simulations in this work were conducted using the single input stream mode for computational simplicity.

The block diagram for the algorithm is shown in Figure 3. This algorithm begins by generating a sequence of bits to form a data set to build a packet. The baseband frame ("BBFrame") will assemble the bits into data packets per frame. Then, the packet will be forwarded for encoding by using the BCH and LDPC encoding algorithms. Once encoded, the packet will enter the interleaver block to convert the encoded bit stream into a memoryless one. The data will be modulated according to the user's parameters, such as QPSK, 8PSK, 16APSK, and 32APSK, once the packet exits the interleaver block. The transmitted signal will then pass through the AWGN channel. The post-AWGN received signal will be demodulated, deinterleved, and decoded. The E_s/N_o in dB will be measured at $P_b = 10^{-5}$. Finally, the data will be put into the BBFrame to assemble the data back together in sequence. The algorithm runs at 50 iterations for LDPC decoding at each ACM mode to obtain an average measured E_s/N_o and the BER at each point until this runs past $P_b \leq 10^{-5}$. Figure 4, Figure 5, Figure 6, and Figure 7, show the simulation BER vs E_s/N_o results for each ACM mode [3].

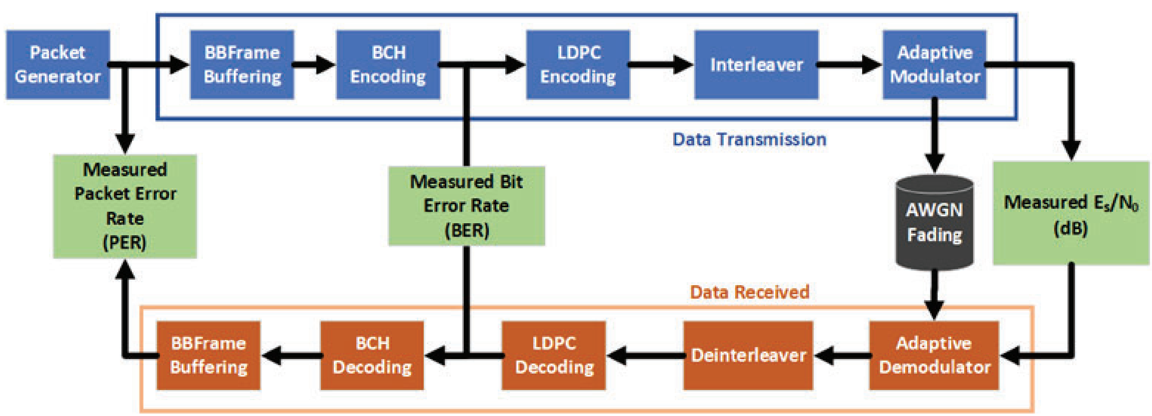

Figure 3. DVB-S2 MATLAB Flow Diagram

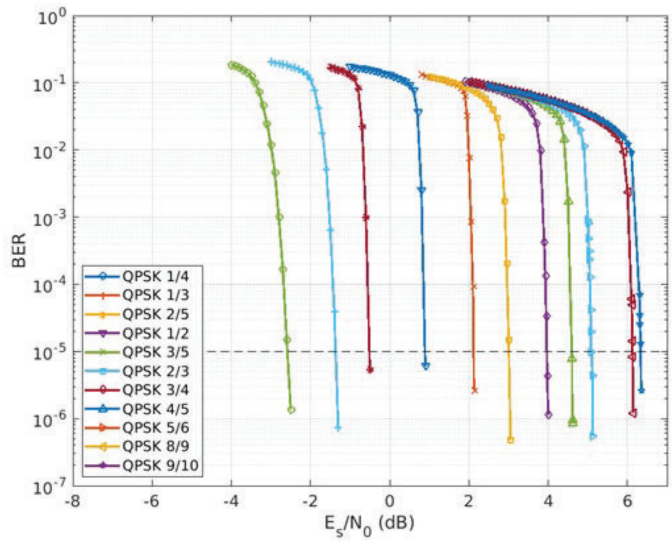

Figure 4. DVB-S2 with QPSK

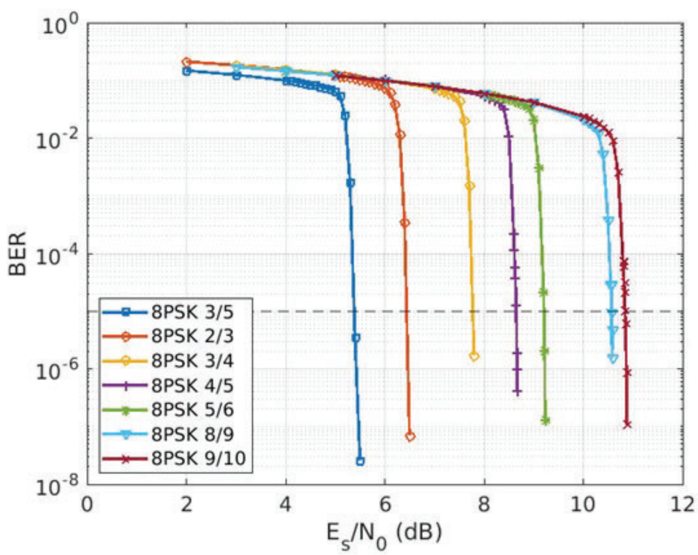

Figure 5. DVB-S2 with 8PSK

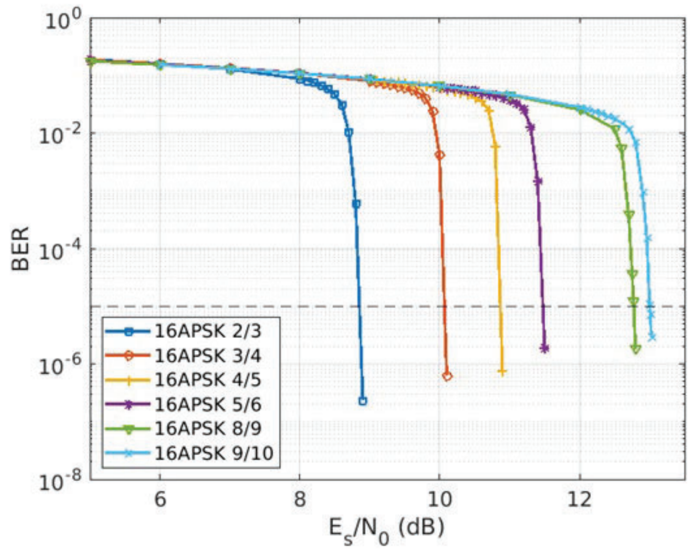

Figure 6. DVB-S2 with 16APSK

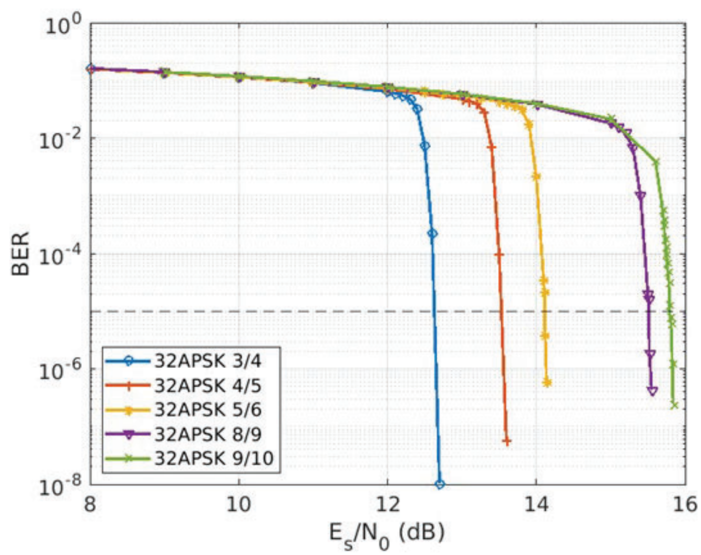

Figure 7. DVB-S2 with 32APSK

Each ACM mode is ranked from the highest E_s/N_o to the lowest required at $P_b = 10^{-5}$. There are 28 different ACM modes in the DVB-S2. Observe from the third column in Table 2 that the required $(E_s/N_o)_i$ to meet 10^{-5} BER decreases as i increases. The highest bandwidth efficient ACM mode is the worst energy-efficient ACM mode and vice versa. The highest required $(E_s/N_o)_i$ ACM mode, i.e., worst energy-efficient ACM mode, will be assigned to ACM mode index $i = 0$ because it is the highest bandwidth efficient ACM mode, and the lowest required $(E_s/N_o)_i$ ACM mode will be assigned to $i = 27$.

Table 2. Required $(E_s/N_o)_i$ at BER P_b=10^{-5} and BWE η_i

Mode Index i	ACM Mode i	Required $(E_s/N_0)_i$ (dB) at $P_b = 10^{-5}$	$\eta_i = R_c \log_2 M(i)$ (bit/s/Hz)	$\Delta\,(E_s/N_0)_i = (E_s/N_0)_{i-1} - (E_s/N_0)_i$ (dB)	$x_i = (E_s/N_0)_0 - (E_s/N_0)_i$ (dB)
27	QPSK 1/4	–2.573	0.500	1.208	18.372
26	QPSK 1/3	–1.365	0.667	0.838	17.164
25	QPSK 2/5	–0.527	0.800	1.392	16.326
24	QPSK 1/2	0.865	1.000	1.227	14.934
23	QPSK 3/5	2.092	1.200	0.892	13.707
22	QPSK 2/3	2.984	1.333	0.981	12.815
21	QPSK 3/4	3.965	1.500	0.614	11.834
20	QPSK 4/5	4.579	1.600	0.506	11.220
19	QPSK 5/6	5.085	1.667	0.300	10.714
18	8PSK 3/5	5.385	1.800	0.770	10.414
17	QPSK 8/9	6.155	1.778	0.170	9.644
16	QPSK 9/10	6.325	1.800	0.125	9.474
15	8PSK 2/3	6.450	2.000	1.321	9.349
14	8PSK 3/4	7.771	2.250	1.089	8.028
13	16APSK 2/3	8.860	2.667	0.357	6.939
12	8PSK 5/6	9.217	2.500	0.903	6.582
11	16APSK 3/4	10.120	3.000	0.438	5.679
10	8PSK 8/9	10.558	2.667	0.287	5.241
9	8PSK 9/10	10.845	2.700	0.086	4.954
8	16APSK 4/5	10.931	3.200	0.579	4.868
7	16APSK 5/6	11.510	3.333	1.125	4.289
6	32APSK 3/4	12.635	3.750	0.133	3.164
5	16APSK 8/9	12.768	3.556	0.132	3.031
4	16APSK 9/10	12.900	3.600	0.631	2.899
3	32APSK 4/5	13.531	4.000	0.591	2.268
2	32APSK 5/6	14.122	4.167	1.377	1.677
1	32APSK 8/9	15.499	4.444	0.300	0.300
0	32APSK 9/10	15.799	4.500	n/a	0.000

Also, refer to the fourth column in Table 2. The BWE η_i of ACM mode i is also decreasing as i increases in general, and is found as

$$\eta_i = R_c(i)\log_2(M(i)) \text{ (bits/s/Hz).} \tag{1}$$

This can be explained as follows: $R_c(i)$ and $M(i)$ are, respectively, the i-th ACM mode's code rate (i.e., number of information bits/coded bit in a codeword), found in Table 1, and the number of constellation points, e.g., $M(i)$ = {32, 16, 8, 4} for 32APSK, 16APSK, 8PSK, and QPSK, respectively, in BWE decreasing order. Hence, the $\log_2(M(i))$ represents the number of coded bits per symbol transmission, and a symbol takes T_s seconds to transmit. Thus, the BWE (bits/s/Hz) in

Eq. (1) is the BWE after normalization with BW = $1/T_s$ (Hz). In other words, the unit of $\eta_i = R_c(i)\log_2(M(i))$ is (information bits/coded bit) × (coded bits/symbol) × (symbols/T_s seconds)/(BW = $1/T_s$), which is equal to (bits/s/Hz).

Figure 8 shows the exceedance probability, i.e., $Pr(P_{RX}(\text{dBm}) > p_{RX})$, versus the receive measured power in dBm for the W/V-band terrestrial link experiment (WTLE) link, based on measurement data for the period of 2019 at the Air Force Research Laboratory. Here, the upper case P_{RX} and the lower case p_{RX} represent the received measured power random variable and its realization, respectively. The received measured power data are listed in Table 3 through Table 10. The lowest and highest receive measured power are respectively, -118 dBm and -40 dBm, which correspond to 78 dB and 0 dB attenuation, respectively. The highest receive power, -40 dBm, occurs when the channel attenuation is caused by only the free-space path loss, i.e., the experimental signal path is in the line-of-sight, the weather is clear, and the surrounding scattering and fading effects are negligible. The additional attenuation can occur if the weather is bad. Hence, the received power can be smaller than -40 dBm. Thus, this highest receive power of -40 dBm corresponds to 0 dB attenuation and the lowest receive measured power of -118 dBm corresponds to 78 dB attenuation.

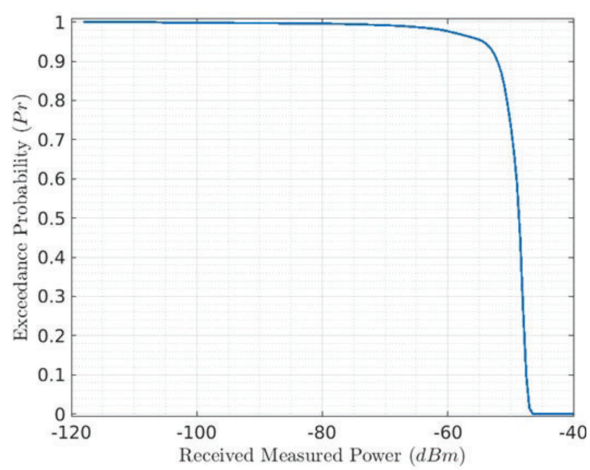

Figure 8. Exceedance Probability vs Received Measured Power (dBm)

Table 3. Exceedance Probability, Measured Power, and Attenuation (78 – 68.5 dB)

P_r	Received Measured Power (dBm)	Attenuation (dB)
1.00000000	–118.0	78.0
0.99999993	–117.5	77.5
0.99999990	–117.0	77.0
0.99999967	–116.5	76.5
0.99999964	–116.0	76.0
0.99999932	–115.5	75.5
0.99999866	–115.0	75.0
0.99999798	–114.5	74.5
0.99999648	–114.0	74.0
0.99999426	–113.5	73.5
0.99999081	–113.0	73.0
0.99998660	–112.5	72.5
0.99998132	–112.0	72.0
0.99997584	–111.5	71.5
0.99997060	–111.0	71.0
0.99996463	–110.5	70.5
0.99995886	–110.0	70.0
0.99995110	–109.5	69.5
0.99993891	–109.0	69.0
0.99991495	–108.5	68.5

Table 4. Exceedance Probability, Measured Power, and Attenuation (68 – 58.5 dB)

P_r	Received Measured Power (dBm)	Attenuation (dB)
0.99986175	–108.0	68.0
0.99976464	–107.5	67.5
0.99961390	–107.0	67.0
0.99941023	–106.5	66.5
0.99916834	–106.0	66.0
0.99888793	–105.5	65.5
0.99858258	–105.0	65.0
0.99828789	–104.5	64.5
0.99803763	–104.0	64.0
0.99785038	–103.5	63.5
0.99773710	–103.0	63.0
0.99766812	–102.5	62.5
0.99762692	–102.0	62.0
0.99760058	–101.5	61.5
0.99757982	–101.0	61.0
0.99755885	–100.5	60.5
0.99753907	–100.0	60.0
0.99752039	–99.5	59.5
0.99749992	–99.0	59.0
0.99748062	–98.5	58.5

Table 5. Exceedance Probability, Measured Power, and Attenuation (58 – 48.5 dB)

P_r	Received Measured Power (dBm)	Attenuation (dB)
0.99746292	–98.0	58.0
0.99744473	–97.5	57.5
0.99742751	–97.0	57.0
0.99740887	–96.5	56.5
0.99738856	–96.0	56.0
0.99736972	–95.5	55.5
0.99734977	–95.0	55.0
0.99732832	–94.5	54.5
0.99730713	–94.0	54.0
0.99728480	–93.5	53.5
0.99726133	–93.0	53.0
0.99723900	–92.5	52.5
0.99721448	–92.0	52.0
0.99719078	–91.5	51.5
0.99716444	–91.0	51.0
0.99713423	–90.5	50.5
0.99710049	–90.0	50.0
0.99706515	–89.5	49.5
0.99702447	–89.0	49.0
0.99697798	–88.5	48.5

Table 6. Exceedance Probability, Measured Power, and Attenuation (48 – 38.5 dB)

P_r	Received Measured Power (dBm)	Attenuation (dB)
0.99693146	–88.0	48.0
0.99688126	–87.5	47.5
0.99682473	–87.0	47.0
0.99676645	–86.5	46.5
0.99670526	–86.0	46.0
0.99664280	–85.5	45.5
0.99657875	–85.0	45.0
0.99651195	–84.5	44.5
0.99643939	–84.0	44.0
0.99636190	–83.5	43.5
0.99628337	–83.0	43.0
0.99620513	–82.5	42.5
0.99612295	–82.0	42.0
0.99603500	–81.5	41.5
0.99593672	–81.0	41.0
0.99583563	–80.5	40.5
0.99572981	–80.0	40.0
0.99561601	–79.5	39.5
0.99549549	–79.0	39.0
0.99535946	–78.5	38.5

Table 7. Exceedance Probability, Measured Power, and Attenuation (38 – 28.5 dB)

P_r	Received Measured Power (dBm)	Attenuation (dB)
0.99522196	–78.0	38.0
0.99508687	–77.5	37.5
0.99494445	–77.0	37.0
0.99477806	–76.5	36.5
0.99461093	–76.0	36.0
0.99443076	–75.5	35.5
0.99424495	–75.0	35.0
0.99406432	–74.5	34.5
0.99388845	–74.0	34.0
0.99366870	–73.5	33.5
0.99342138	–73.0	33.0
0.99316033	–72.5	32.5
0.99289872	–72.0	32.0
0.99262121	–71.5	31.5
0.99234213	–71.0	31.0
0.99204324	–70.5	30.5
0.99175132	–70.0	30.0
0.99143733	–69.5	29.5
0.99107884	–69.0	29.0
0.99067811	–68.5	28.5

Table 8. Exceedance Probability, Measured Power, and Attenuation (28 – 18.5 dB)

P_r	Received Measured Power (dBm)	Attenuation (dB)
0.99026538	–68.0	28.0
0.98981861	–67.5	27.5
0.98933609	–67.0	27.0
0.98880258	–66.5	26.5
0.98816590	–66.0	26.0
0.98750949	–65.5	25.5
0.98688040	–65.0	25.0
0.98624757	–64.5	24.5
0.98558164	–64.0	24.0
0.98483562	–63.5	23.5
0.98404133	–63.0	23.0
0.98313636	–62.5	22.5
0.98205875	–62.0	22.0
0.98098814	–61.5	21.5
0.97979158	–61.0	21.0
0.97819138	–60.5	20.5
0.97633140	–60.0	20.0
0.97449424	–59.5	19.5
0.97257484	–59.0	19.0
0.97066844	–58.5	18.5

Table 9. Exceedance Probability, Measured Power, and Attenuation (18 – 8.5 dB)

P_r	Received Measured Power (dBm)	Attenuation (dB)
0.96849783	–58.0	18.0
0.96642919	–57.5	17.5
0.96417786	–57.0	17.0
0.96205012	–56.5	16.5
0.95993809	–56.0	16.0
0.95755262	–55.5	15.5
0.95460480	–55.0	15.0
0.95083885	–54.5	14.5
0.94579017	–54.0	14.0
0.93856623	–53.5	13.5
0.92845607	–53.0	13.0
0.91469868	–52.5	12.5
0.89607941	–52.0	12.0
0.87208997	–51.5	11.5
0.83712903	–51.0	11.0
0.79173591	–50.5	10.5
0.73854860	–50.0	10.0
0.67406963	–49.5	9.5
0.59045239	–49.0	9.0
0.45766665	–48.5	8.5

Table 10. Exceedance Probability, Measured Power, and Attenuation (8 – 0 dB)

P_r	Received Measured Power (dBm)	Attenuation (dB)
0.26347283	–48.0	8.0
0.09690267	–47.5	7.5
0.01545946	–47.0	7.0
0.00073549	–46.5	6.5
0.00012123	–46.0	6.0
0.00002774	–45.5	5.5
0.00000838	–45.0	5.0
0.00000310	–44.5	4.5
0.00000101	–44.0	4.0
0.00000039	–43.5	3.5
0.00000016	–43.0	3.0
0.00000016	–42.5	2.5
0.00000013	–42.0	2.0
0.00000010	–41.5	1.5
0.00000003	–41.0	1.0
0.00000000	–40.5	0.5
0.00000000	–40.0	0.0

Therefore, the highest ACM mode $i = 0$, i.e., 32APSK 9/10, will be assigned when attenuation is 0 dB, i.e., the received power is -40 dBm. The next highest ACM mode, 32APSK 8/9, will be assigned if the attenuation is between 0 dB and 0.3 dB, from the last column in Table 2. If the attenuation is between 0.3 dB and (0.3 + 1.377 = 1.677) dB, then the next highest ACM mode 32APSK 5/6 will be assigned, and so on. Hence, the received measured power random variable P_{RX} (dBm) shown in the horizontal axis of Figure 8 will be converted to the attenuation random variable X in dB shown in Figure 9.

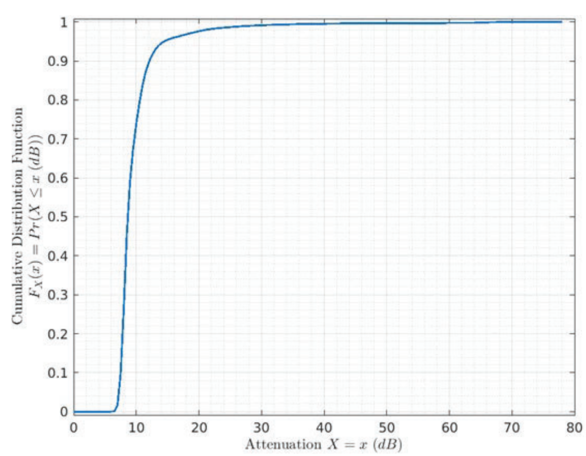

Figure 9. CDF F_X of Attenuation Random Variable X (dB)

This is accomplished by subtracting the observed power level from an offset received power value (-40 dBm for this study) to achieve an attenuation figure X in dB using the relation

$$X = -40 - P_{RX}. \tag{2}$$

Using Eq. (2), the exceedance probability of the receive measured power P_{RX} in dBm and the CDF of the attenuation random variable X in dB can be related as

$$\Pr(P_{RX} \geq p_{RX}) = \Pr(P_{RX} = -X - 40 \geq p_{RX}) \tag{3}$$

$$= \Pr(X \leq x = -40 - p_{RX}) = F_X(x). \tag{4}$$

Experimentally, the CDF of the attenuation random variable X in dB is obtained as

$$F_X(x) = \Pr(X \leq x) \approx \frac{|AData{:}AData \leq x|}{|AData|} \tag{5}$$

where |A| denotes the cardinality of a set A, and "AData" is a set that contains all attenuation measurements during the period of interest from the W/V-band experimental link. The value of X in dB is defined in Eq. (2) and bounded by the extrema of the AData set. Figure 9 shows the corresponding CDF of the attenuation random variable X in dB.

Before applying the CDF of the attenuation in dB in Figure 9, the difference of the required $(E_s/N_o)_i$ at $P_b \leq 10^{-5}$ between ACM mode i-1 and i, except for ACM mode i=0, is computed using the third column of Table 2 and is listed in the fifth column, i=1, …, 27:

$$\Delta(E_s/N_0)_i = (E_s/N_0)_{i-1} - (E_s/N_0)_i. \tag{6}$$

This difference will be used to find the best ACM mode from the current ACM mode i, depending on the attenuation. It is desirable to use an ACM mode of a lower index for a higher BWE, as long as the received SNR meets the minimum required SNR shown in Table 2. Refer to the fourth column of Table 2, which lists the BWE η_i of each ACM mode i using Eq. (1).

If the received SNR is between $(Es/N_o)_{i-1}$ and $(E_s/N_o)_i$, then it will use ACM mode i to maximize the BWE for the following reasons: (a) because the SNR is not sufficient to use ACM mode i-1 and achieve $P_b \leq 10^{-5}$, but the SNR is sufficient to support ACM mode i and achieve $P_b \leq 10^{-5}$; and (b) because an ACM mode with a lower mode index yields a higher BWE, as shown in the fourth column of Table 2.

Instead of the Rx measured SNR, only the CDF of the measured attenuation is available; hence, the attenuation random variable X must be utilized to compute the BWE of the terrestrial W/V-band. The best bandwidth efficient ACM mode 0 in the DVB-S2 will be transmitted when there is no attenuation, i.e., X = 0 dB. Also, note that the sum of the differences $\Delta(E_s/N_0)_j$ in Eq. (6) is just the difference between the first term and the last term in the sum, i.e.,

$$\sum_{j=1}^{i} \Delta(E_s/N_0)_j = (E_s/N_0)_0 - (E_s/N_0)_i, \tag{7}$$

because the middle terms are cancelled by Eq. (6). This sum corresponds to the cumulative attenuation from ACM mode 0 to ACM mode i. Therefore, this sum also indicates which ACM mode will be the best to use for a given attenuation X. In other words, if the attenuation X is

$$(E_s/N_0)_0 - (E_s/N_0)_{i-1} \leq X < (E_s/N_0)_0 - (E_s/N_0)_i \tag{8}$$

i.e., if

$$\sum_{j=1}^{i-1} \Delta(E_s/N_0)_j \leq X < \sum_{j=1}^{i} \Delta(E_s/N_0)_j \tag{9}$$

for $i = 0, \ldots, 27$, then the transmitter will use ACM mode i. The sixth column of Table 2 lists $x_i = (E_s/N_0)_0 - (E_s/N_0)_i$ in dB for the system to use ACM mode i when the attenuation X satisfies the inequality in Eq. (9) and the link margin $x_{LM} = 0$ dB. As the attenuation X varies in time, the best ACM mode i will be selected, corresponding to the attenuation X using Eq. (9) to maximize the BWE.

The next necessary information in the BWE computation is the probability of using p_i of ACM mode i. The measured CDF shown previously in Figure 9 can provide this information on these probabilities, p_i, with which ACM mode i is being used, as

$$p_i = PR(ACM_i\ used) = F_X(X = x_i) - F_X(X = x_{i-1}) \tag{10}$$

for $i = 0, \ldots, 27$, where $F_X(x_i)$ is defined in Eq. (5). This is because ACM mode i will be selected if the attenuation random variable X satisfies Eq. (8). ACM mode 0 has the highest BWE and will be used at attenuation $X = 0$ dB with $p_0 = F_X(x_0 = 0)$ probability, and ACM mode 27 has the lowest BWE and will be used at attenuation $X \geq (15.799 - (-2.573)) = 18.372$ dB. Figure 10 provides a sketch of CDF $F_X(x_i)$ for attenuation $X = x_i$ dB and the corresponding probability, p_i, assuming that ACM mode 0 is used at attenuation $X = 0$ dB.

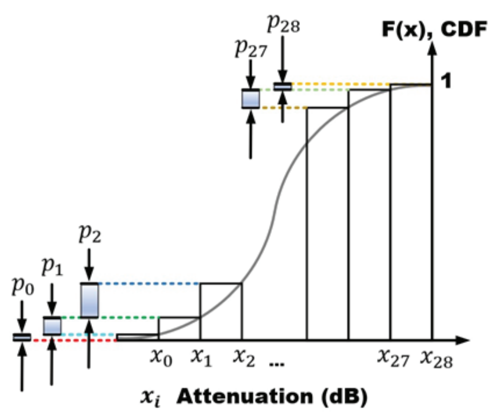

Figure 10. Cumulative Distribution Function vs Attenuation (dB)

In typical terrestrial and satellite communications, an extra power called a link margin in dB has been included for the transmit signal power calculation so that the system can tolerate an additional received power loss due to attenuation and other loss such as antenna pointing, circuit implementation, etc. In this report, the link margin represents the extra receive power needed to tolerate additional loss due to attenuation only.

Four cases {A, B, C, D} of different link margin attenuations x_{LM} {0, 10, 28, 78} dB, respectively, will be considered for demonstration. Other link margins can also be considered by simply shifting the link margin value. A DVB-S2 receiver will perform normally with the highest ACM mode i = 0 until the attenuation X in the horizontal axis of Figure 9 reaches the link margin attenuation x_{LM}. In other words, the highest bandwidth efficient ACM mode 32APSK 9/10 will have the receive SNR $(E_s/N_0) \geq 15.799$ dB and $P_b \leq 10^{-5}$. Therefore, in this report, the highest ACM mode 32APSK 9/10 will always be transmitted at attenuation $X = x_{LM}$ with probability

$$p_0 = F_x(X = x_{LM}) \text{ if } X \leq x_{LM}. \tag{11}$$

Let

$$x_i = (E_s/N_0)_0 - (E_s/N_0)_i \text{ , } i \geq 1 \text{ and } x_0 = 0. \tag{12}$$

Then, a lower ACM mode i satisfying both conditions -- the required $P_b \leq 10^{-5}$ and the smallest positive $0 \leq i \leq 27$ -- will be selected if

$$x_{LM} + x_{i-1} \leq X < x_{LM} + x_i \tag{13}$$

with probability

$$p_i = F_X(X = x_{LM} + x_i) - F_X(X = x_{LM} + x_{i-1}). \tag{14}$$

Since the link margin is predetermined by the system, the best ACM mode i that closely satisfies $(E_s/N_o)_i$ in Eq. (12) can be precomputed by searching for x_i in Table 2. For example, if the link margin of a W/V-band communication link is $x_{LM} = 10$ dB and the attenuation is $X \leq x_{LM} \leq 10$ dB, then the highest mode 32APSK 9/10 in Table 2 will be transmitted at $X \leq x_{LM} \leq 10$ dB with probability

$$p_0 = F_X(X = x_{LM} = 10) = 0.73854860 \tag{15}$$

which is from the last column of Table 3 through Table 10, with $X = 10$ dB, i.e., received measured power $p_{RX} = -40 - X = -50$ dBm. If the attenuation is between x_{LM} and $x_{LM} + x_1$, i.e., $10 < X \leq 10.3$, then the next highest ACM 32APSK 8/9 mode will be transmitted with probability

$$p_1 = F_X(X = x_{LM} + x_1) - F_X(X = x_{LM} + x_0) \tag{16}$$

$$= F_X(10.3\ dB) - F_X(10\ dB) \approx 0.79 - 0.74 = 0.05 \tag{17}$$

for $i = 1$ from Table 2 and Table 3 through Table 10. The other incremental probability is computed as Eq. (14) for $i = 0, ..., 27$. The lowest bandwidth efficient ACM mode 27 will be used if $X > (x_{LM} + x_{27})$ with probability

$$p_{28} = 1 - F_X(x_{LM} + x_{27}) = 1 - F_X(27.164) \tag{18}$$

$$\approx 1 - 0.98933609 = 0.01066391. \tag{19}$$

Table 11, Table 12, Table 13, and Table 14 list p_i, $F_X(x_i)$, and η_i for Case A, B, C, and D, respectively. The link margin, x_{LM}, for each case is {0, 10, 28, 78} dB, respectively. Note that in Table 2 through Table 10 the required SNR, E_s/N_o, to achieve BER = 10^{-5} is not quantized, while the measured attenuation in dB is quantized with a 0.5 dB step. Therefore, there are slight differences in p_i and $F_X(x_i)$ between Table 2 through Table 10 and Table 11 through Table 14. This quantization effect on BWE computation is neglected.

Table 11. Case A: 8PSK 2⁄3 Transmitted at $X = x_{LM} = 0$ (dB) Attenuation

Mode Index, i	ACM Mode, i	p_i = Pr(ACM$_i$)	$CDF(x_i)$ at ACM_i	$\eta_i \times p_i$ $(bits/s/Hz)$	$\eta_i \times p_i \times (1 - P_b)$ $(bits/s/Hz)$	$\eta_i \times p_i \times (1 - P_b) \times BW$ $(bits/s)$
27	QPSK 1/4	0.0064905	0.0064905	0.0032452	0.0032452	16120958
26	QPSK 1/3	0.0021277	0.0086183	0.0014185	0.0014184	7077314
25	QPSK 2/5	0.0044975	0.0131158	0.0035980	0.0035979	17908900
24	QPSK 1/2	0.0160385	0.0291543	0.0160385	0.0160384	78905893
23	QPSK 3/5	0.0101101	0.0392645	0.0121321	0.0121320	60047066
22	QPSK 2/3	0.0323766	0.0716412	0.0431688	0.0431684	208853993
21	QPSK 3/4	0.0589503	0.1305915	0.0884255	0.0884246	416060085
20	QPSK 4/5	0.0453931	0.1759847	0.0726289	0.0726282	346657173
19	QPSK 5/6	0.0000000	0.1759847	0.0000000	0.0000000	0
18	8PSK 3/5	0.1176662	0.2936509	0.2117993	0.2117971	934378985
17	QPSK 8/9	0.0000000	0.2936509	0.0000000	0.0000000	0
16	QPSK 9/10	0.0000000	0.2936509	0.0000000	0.0000000	0
15	8PSK 2/3	0.4105968	0.7042477	0.8211936	0.8211853	2420046474
14	8PSK 3/4	0.2480133	0.9522611	0.5580301	0.5580245	2098134862
13	16APSK 2/3	0.0147239	0.9669851	0.0392639	0.0392635	193427047
12	8PSK 5/6	0.0007077	0.9676928	0.0017693	0.0017693	8840501
11	16APSK 3/4	0.0000000	0.9676928	0.0000000	0.0000000	0
10	8PSK 8/9	0.0000193	0.9677122	0.0000516	0.0000516	258173
9	8PSK 9/10	0.0000052	0.9677175	0.0000142	0.0000142	71292
8	16APSK 4/5	0.0000000	0.9677175	0.0000000	0.0000000	0
7	16APSK 5/6	0.0000029	0.9677204	0.0000097	0.0000097	48897
6	32APSK 3/4	0.0000000	0.9677204	0.0000000	0.0000000	0
5	16APSK 8/9	0.0000000	0.9677204	0.0000000	0.0000000	0
4	16APSK 9/10	0.0000000	0.9677204	0.0000000	0.0000000	0
3	32APSK 4/5	0.0000000	0.9677205	0.0000002	0.0000002	1304
2	32APSK 5/6	0.0000001	0.9677206	0.0000004	0.0000004	2037
1	32APSK 8/9	0.0000000	0.9677206	0.0000000	0.0000000	0
0	32APSK 9/10	0.0000000	0.9677206	0.0000000	0.0000000	0

$\sum_{0}^{27} p_i$
1.000000

$E[\eta]$ = Normalized BWE $(bits/s/Hz)$	$E[\eta] \times BW =$ $(Gbits/s)$
1.8728	6.8068

Table 12. Case B: 32APSK 9⁄10 Transmitted at $X = x_{LM} = 10$ (dB) Attenuation

Mode Index, i	ACM Mode, i	p_i = Pr(ACM$_i$)	$CDF(x_i)$ at ACM_i	$\eta_i \times p_i$ $(bits/s/Hz)$	$\eta_i \times p_i \times (1-P_b)$ $(bits/s/Hz)$	$\eta_i \times p_i \times (1-P_b) \times BW$ $(bits/s)$
27	QPSK 1/4	0.0106639	1.0000000	0.0053320	0.0053319	26659514
26	QPSK 1/3	0.0005335	0.9893361	0.0003557	0.0003557	1778344
25	QPSK 2/5	0.0019222	0.9888026	0.0015377	0.0015377	7688627
24	QPSK 1/2	0.0020448	0.9868804	0.0020448	0.0020448	10223794
23	QPSK 3/5	0.0007943	0.9848356	0.0009532	0.0009531	4765736
22	QPSK 2/3	0.0019826	0.9840413	0.0026434	0.0026434	13217075
21	QPSK 3/4	0.0022672	0.9820587	0.0034008	0.0034007	17003581
20	QPSK 4/5	0.0016002	0.9797916	0.0025603	0.0025603	12801469
19	QPSK 5/6	0.0000000	0.9781914	0.0000000	0.0000000	0
18	8PSK 3/5	0.0036971	0.9781914	0.0066548	0.0066548	33273897
17	QPSK 8/9	0.0000000	0.9744942	0.0000000	0.0000000	0
16	QPSK 9/10	0.0000000	0.9744942	0.0000000	0.0000000	0
15	8PSK 2/3	0.0059964	0.9744942	0.0119928	0.0119927	59963531
14	8PSK 3/4	0.0043200	0.9684978	0.0097199	0.0097198	48599124
13	16APSK 2/3	0.0021277	0.9641779	0.0056740	0.0056739	28369619
12	8PSK 5/6	0.0044975	0.9620501	0.0112437	0.0112436	56218154
11	16APSK 3/4	0.0029478	0.9575526	0.0088435	0.0088434	44216939
10	8PSK 8/9	0.0000000	0.9546048	0.0000000	0.0000000	0
9	8PSK 9/10	0.0000000	0.9546048	0.0000000	0.0000000	0
8	16APSK 4/5	0.0037660	0.9546048	0.0120510	0.0120509	60254634
7	16APSK 5/6	0.0223828	0.9508388	0.0746093	0.0746085	373042598
6	32APSK 3/4	0.0000000	0.9284561	0.0000000	0.0000000	0
5	16APSK 8/9	0.0000000	0.9284561	0.0000000	0.0000000	0
4	16APSK 9/10	0.0137574	0.9284561	0.0495266	0.0495261	247630507
3	32APSK 4/5	0.0426087	0.9146987	0.1704348	0.1704331	852165602
2	32APSK 5/6	0.0803541	0.8720900	0.3348086	0.3348052	1674026200
1	32APSK 8/9	0.0531873	0.7917359	0.2363880	0.2363857	1181928352
0	32APSK 9/10	0.7385486	0.7385486	3.3234687	3.3234355	16617177412

$\sum_0^{27} p_i$
1.000000

$E[\eta]$ = Normalized BWE $(bits/s/Hz)$	$E[\eta] \times BW = (Gbits/s)$
4.274	21.371

Table 13. Case C: 32APSK 9⁄10 Transmitted at $X = x_{LM}$ = 28 (dB) Attenuation

Mode Index, i	ACM Mode, i	p_i = Pr(ACM$_i$)	$CDF(x_i)$ at ACM_i	$\eta_i \times p_i$ $(bits/s/Hz)$	$\eta_i \times p_i \times (1-P_b)$ $(bits/s/Hz)$	$\eta_i \times p_i \times (1-P_b) \times BW$ $(bits/s)$
27	QPSK 1/4	0.0034213	1.0000000	0.0017106	0.00171061	8553051
26	QPSK 1/3	0.0000668	0.9965787	0.0000445	0.00004452	222646
25	QPSK 2/5	0.0002286	0.9965119	0.0001828	0.00018286	914316
24	QPSK 1/2	0.0002484	0.9962833	0.0002483	0.00024836	1241831
23	QPSK 3/5	0.0000983	0.9960350	0.0001179	0.00011794	589703
22	QPSK 2/3	0.0002069	0.9959367	0.0002758	0.00027586	1379341
21	QPSK 3/4	0.0002343	0.9957298	0.0003514	0.00035147	1757372
20	QPSK 4/5	0.0001360	0.9954954	0.0002176	0.00021765	1088260
19	QPSK 5/6	0.0000000	0.9953594	0.0000000	0.00000000	0
18	8PSK 3/5	0.0002726	0.9953594	0.0004906	0.00049065	2453280
17	QPSK 8/9	0.0000000	0.9950868	0.0000000	0.00000000	0
16	QPSK 9/10	0.0000000	0.9950868	0.0000000	0.00000000	0
15	8PSK 2/3	0.0004759	0.9950868	0.0009518	0.00095186	4759347
14	8PSK 3/4	0.0003660	0.9946109	0.0008234	0.00082345	4117283
13	16APSK 2/3	0.0001806	0.9942449	0.0004816	0.00048167	2408360
12	8PSK 5/6	0.0003956	0.9940643	0.0009890	0.00098903	4945157
11	16APSK 3/4	0.0002473	0.9936687	0.0007419	0.00074196	3709846
10	8PSK 8/9	0.0000000	0.9934213	0.0000000	0.00000000	0
9	8PSK 9/10	0.0000000	0.9934213	0.0000000	0.00000000	0
8	16APSK 4/5	0.0002610	0.9934213	0.0008353	0.00083535	4176751
7	16APSK 5/6	0.0008182	0.9931603	0.0027273	0.00272727	13636398
6	32APSK 3/4	0.0000000	0.9923421	0.0000000	0.00000000	0
5	16APSK 8/9	0.0000000	0.9923421	0.0000000	0.00000000	0
4	16APSK 9/10	0.0002989	0.9923421	0.0010760	0.00107601	5380083
3	32APSK 4/5	0.0006059	0.9920432	0.0024236	0.00242361	12118079
2	32APSK 5/6	0.0007592	0.9914373	0.0031634	0.00316339	15816950
1	32APSK 8/9	0.0004127	0.9906781	0.0018343	0.00183434	9171703
0	32APSK 9/10	0.9902654	0.9902653	4.4561941	4.45614963	22280748150

$\sum_0^{27} p_i$
1.000000

$E[\eta]$ = Normalized BWE $(bits/s/Hz)$	$E[\eta] \times BW =$ $(Gbits/s)$
4.476	22.379

Table 14. Case D: 32APSK 9/10 Transmitted at $X = x_{LM}$ = 78 (dB) Attenuation

Mode Index, i	ACM Mode, i	p_i = Pr(ACM$_i$)	$CDF(x_i)$ at ACM_i	$\eta_i \times p_i$ $(bits/s/Hz)$	$\eta_i \times p_i \times (1-P_b)$ $(bits/s/Hz)$	$\eta_i \times p_i \times (1-P_b) \times BW$ $(bits/s)$
27	QPSK 1/4	-	-	-	-	-
26	QPSK 1/3	-	-	-	-	-
25	QPSK 2/5	-	-	-	-	-
24	QPSK 1/2	-	-	-	-	-
23	QPSK 3/5	-	-	-	-	-
22	QPSK 2/3	-	-	-	-	-
21	QPSK 3/4	-	-	-	-	-
20	QPSK 4/5	-	-	-	-	-
19	QPSK 5/6	-	-	-	-	-
18	8PSK 3/5	-	-	-	-	-
17	QPSK 8/9	-	-	-	-	-
16	QPSK 9/10	-	-	-	-	-
15	8PSK 2/3	-	-	-	-	-
14	8PSK 3/4	-	-	-	-	-
13	16APSK 2/3	-	-	-	-	-
12	8PSK 5/6	-	-	-	-	-
11	16APSK 3/4	-	-	-	-	-
10	8PSK 8/9	-	-	-	-	-
9	8PSK 9/10	-	-	-	-	-
8	16APSK 4/5	-	-	-	-	-
7	16APSK 5/6	-	-	-	-	-
6	32APSK 3/4	-	-	-	-	-
5	16APSK 8/9	-	-	-	-	-
4	16APSK 9/10	-	-	-	-	-
3	32APSK 4/5	-	-	-	-	-
2	32APSK 5/6	-	-	-	-	-
1	32APSK 8/9	-	-	-	-	-
0	32APSK 9/10	0.9902654	1.000	4.4561941	4.500	22499775000

$\sum_{0}^{27} p_i$	$E[\eta]$ = Normalized BWE $(bits/s/Hz)$	$E[\eta] \times BW = (Gbits/s)$
1.000000	4.476	22.379

If channel attenuation X is larger than 0 dB and smaller than or equal to the maximum difference in the required SNR $(E_s/N_0)_{i=0} - (E_s/N_0)_{i=27} = 18.372$ dB, i.e., if the attenuation is smaller than or equal to the difference between the highest and lowest ACM mode in column 3 of Table 2, then there exists an ACM mode where $P_b \leq 10^{-5}$. Since $F_X(x)$ is available from the WTLE measured attenuation shown in Table 3 through Table 10, p_i in Eq. (10) can be found approximately.

The p_i and $F_X(x_i)$ are shown in Figure 11 and Figure 12 for four cases {A, B, C, and D} of x_{LM} = {0, 10, 28, 78} dB, respectively. Furthermore, Table 11, Table 12, Table 13, and Table 14 list i, p_i, η_i, and $p_i \times \eta_i$ for cases A, B, C, and D, respectively, which correspond to Figure 11 and Figure 12.

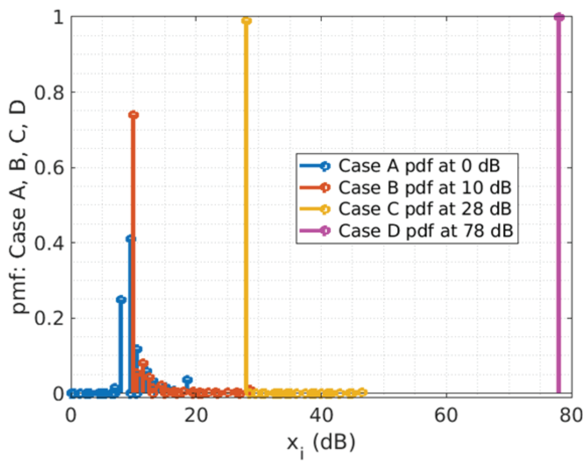

Figure 11. Probability Mass Function vs Attenuation x_i

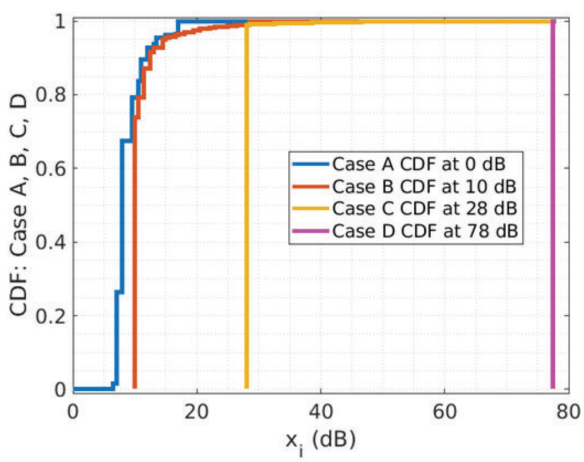

Figure 12. Cumulative Distribution Function vs Attenuation x_i

The average BWE of the W/V-band system in bits/s/Hz is computed as

$$E[\eta] = (1 - P_b)\sum_0^{27} n_i p_i \tag{20}$$

where $(1 - P_b)$ is multiplied to consider only the bits delivered with no errors when the best ACM mode in DVB-S2, depending on the channel attenuation, is transmitted.

Finally, each of the W-band and V-band channels have a contiguous bandwidth, BW = 5 GHz, and the W- and V-bands occupy 81–86 GHz and 71–76 GHz frequency bands, respectively. Hence, BW = 5 GHz is multiplied to the BWE in Eq. (20) to find the average BWE in bits/s and rewritten as

$$E[BWE] = BW \cdot E[\eta] \text{ (bits/s).} \quad (21)$$

4.0 RESULTS AND DISCUSSION

The required SNR E_s/N_o for each ACM mode to achieve BER ≤ 10^{-5} was found through the DVB-S2 system under an AWGN channel environment. Figure 4, Figure 5, Figure 6, Figure 7 indicate the BER versus E_s/N_o for all 28 ACM modes. A dotted line passing through BER ≤ 10^{-5} is shown in each figure, and the corresponding required SNR E_s/N_o for each mode is listed in the third column of Table 2. The bandwidth efficiencies and differences in required E_s/N_o are also listed in Table 2 to relate to the CDF $F_X(x) = \Pr(X < x)$ of the attenuation random variable X in Table 3 through Table 10. In Table 2, each ACM_i mode is ranked from the highest required E_s/N_o ACM mode of i = 0 at $P_b \leq 10^{-5}$ to the lowest for ACM mode of i = 28. The highest ACM mode is 32APSK at code rate 9/10, and the lowest is QPSK at code rate 1/4.

Typically, a higher ACM mode requires a higher cost, i.e., a higher receive SNR E_s/N_o to achieve $P_b \leq 10^{-5}$, even though it shows a higher BWE. Hence, it will be desirable to transmit the highest ACM mode 32APSK 9/10 at attenuation $X = x_{LM}$ under clear weather conditions. Then, for further attenuation from x_{LM} due to rain, the next highest ACM mode is desirable to be transmitted with $P_b \leq 10^{-5}$.

Four cases were considered in this bandwidth efficiency computation. Case A begins at the highest receive measured power -40 dBm (i.e., x_{LM} = 0 dB), Case B begins at -50 dBm (i.e., x_{LM} = 10 dB), Case C begins at -68 dBm (i.e., x_{LM} = 28 dB), and Case D begins at -118 dBm (i.e., x_{LM} = 78 dB).

The probability mass function (pmf), shown previously in Figure 11, versus the further attenuation x_i from x_0 shows the probability of each ACM mode i being used. This further attenuation x_i can be computed using $x_i - x_0 = (E_s/N_0)_0 - (E_s/N_0)_i$ and $x_0 = x_{LM}$, and is associated with ACM mode i. For example, in Case A, $x_0 = x_{LM} = 0$ and $x_{i=1} - x_0 = (E_s/N_0)_0 - (E_s/N_0)_{i=1} =$ 0.3 dB from Table 2. Hence, $x_{i=1} = x_0 + 0.3$ dB $= 0.3$ dB. Observe in Figure 11 for Cases B, C, and D that the largest spike in pmf occurs at ACM mode 32APSK 9/10, which is the highest bandwidth efficient mode according to Table 2.

For Case A, the 8PSK at code rate 2/3 has the highest probability of 0.41059680, and ACM mode i = 16 is used when the link margin is x_{LM} = 0 dB. The BWE of 8PSK at code rate 2/3 is lower than ACM mode 32APSK at code rate 9/10. This is why the average BWE for Case A is worse than that of the other cases B, C, and D. Refer to Case A shown in Table 11.

In Case B, the link margin x_{LM} = 10 dB, corresponding to the peak receive measured power at -50 dBm from $P_{RX} = -X - 40$ dBm, and ACM mode 32APSK at code rate 9/10 has the highest probability of 0.738548604 and will be transmitted at attenuation $X = x_{LM} = 10$ dB. Refer to Case B in Table 12. Data also shows that the product of bandwidth efficiency times the probability of

ACM mode i being used, i.e., $p_i\eta_i$, is the highest at ACM mode 32APSK 9/10. This is why the average BWE for Case B is higher than that for Case A.

In Case C, the link margin was set at x_{LM} = 28 dB, and ACM mode 32APSK 9/10 has the highest probability at 0.99026538. Refer to Case C in Table 13. The average BWE for Case C is slightly higher than that for Case B. In practice, it would be expensive to design the system with the link margin x_{LM} = 28 dB.

In Case D, the link margin was set at x_{LM} = 78 dB, and ACM mode 32APSK 9/10 has the highest probability at 1. Refer to Case D in Table 14. The average BWE for Case D is the highest among all four cases, but slightly higher than that for Cases B and C. In practice, it would be expensive and almost impossible to have a link margin x_{LM} = 78 dB.

Figure 12 shows the CDFs versus attenuation x_i in dB corresponding to the pmfs in Figure 11 for Cases A, B, C, and D. When all p_i's in Figure 11 are added up for each ACM mode, the sum should be equal to 1. The attenuation index range could be used as a sliding rule along the CDF attenuation curve in Figure 9. The pmf for each ACM mode can be quickly calculated, and the highest probability can be found to change the ACM that achieves the best BWE.

Table 15 shows for each case the average BWE (Gbits/s) per antenna beam and the highest probability ACM mode (R_c). Observe that the higher link margin yields a higher BWE. However, this requires a higher cost, e.g., a higher transmitting power, larger antenna size, and lower noise figure, etc. Case A is the worst, and Case D is the best, in the sense of bandwidth efficiency. Case B is the most reasonable out of the four cases for practical application, but the 10 dB link margin for Case B may still be high to achieve in practice.

Table 15. BWE Results with BW=5 GHz

Case	E[η] × BW = Gbps per Antenna Beam	Highest Probability ACM Mode (R_c)
A	6.807	8PSK 2/3
B	21.371	32APSK 9/10
C	22.379	32APSK 9/10
D	22.500	32APSK 9/10

5.0 CONCLUSIONS

In this report, a W/V-band communication system under an AWGN environment was considered with a single transmit antenna and a single receive antenna, i.e., single-input single-output (SISO). The guaranteed average BER was set to 10^{-5}. Then, a method involving how to compute the BWE of the W/V-band system was presented by using the available channel attenuation experiment data and 28 different ACM modes in the DVB-S2 system. It was found that the BWE of the W/V-band system is 4.27 bits/s/Hz and the maximum data rate is 21.37 Gbps per beam at BER = 10^{-5}, when the link margin is 10 dB and the W/V-band channel contiguous BW is 5 GHz.

Compared to the 20 Gbps peak data rates in the existing terrestrial mmWave 5G massive MIMO system at frequencies of 28 GHz and 39 GHz, improvement of the W/V-band is significant. This is because the 5G massive MIMO system employs multiple transmit and receive antennas, e.g., 64 antennas, whereas a single transmit and a single receive antenna were used in the W/V-band experiment. If multiple transmit and receive antennas were used as the 5G massive MIMO, then the BWE of the W/V-band would be much higher. The presented method in this report can be extended to other channel environments, such as Rayleigh and Rician fading, and to other ACM modes, such as those in the protected tactical waveform (PTW) system.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
8PSK	8 Phase Shift Keying
16APSK	16-ary Amplitude Phase Shift Keying
32APSK	32-ary Amplitude Phase Shift Keying
ACM	Adaptive Code Modulation
AFRL	Air Force Research Laboratory
AWGN	Additive White Gaussian Noise
BCH	Bose-Chaudhuri-Hocquenghem
BER	Bit Error Rate
BW	Bandwidth
BWE	Bandwidth Efficiency
CDF	Cumulative Distribution Function
dB	Decibel
dBm	Decibel, referenced to 1 milli-watt
DVB-S2	Digital Video Broadcasting-Satellite Second Generation
E_s/N_o	Quotient of Energy per Symbol and Noise Power Density
FEC	Forward Error Correction
Gbps	Giga Bits Per Second
GHz	Giga Hertz
LDPC	Low Density Parity Check
M(i)	Number of Constellation Points
MIMO	Multiple Input, Multiple Output
P_b	Probability of Bit Error
Pr	Probability
PER	Packet Error Rate

pmf	Probability Mass Function
PTW	Protected Tactical Waveform
QPSK	Quadrature Phase Shift Keying
Rc	Code Rate
Rx	Receive
SISO	Single Input, Single Output
SNR	Signal to Noise Ratio
Ts	Symbol Rate
Tx	Transmit
WTLE	W/V-band Terrestrial Link Experiment

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