Estimation of the Bandwidth of the Communication Channel of 5G Networks Based on Small Cells

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***Abstract*— The article is devoted to the problem of using 5G millimeter waves band (MM WB) in wireless communication systems of the next generation. The aim of the work is to clarify the calculation methods and estimate the availability parameters and performance of communication channels in the millimeter wavelength band when deploying 5G communication network segments in various climatic zones of Ukraine.**

Keywords*— *millimeter wave propagation, 5G, small cells, mobile communication, rain attenuation, IEEE 802.11ad

I. Introduction

The emergence of WiGig technologies and the IEEE 802.11ad new standard for wireless data transfer in 2012 was determined by the need to increase the multimedia data transfer rates and the widespread introduction of high-quality video information playback technologies with high resolution (HDTV, UHD) significantly. The use of the 60 GHz band made it possible to expand the bandwidth of the communication channel significantly up to 2 GHz. It means the speed of information transfer, which contributes to the massive introduction of the Internet of Things (IoT). High data transfer rates using WiGig technology were achieved inside premises at short distances (within 10-15 m), which was sufficient, for example, for virtual or augmented reality (VR/AR) technologies [1,2].

However, scenarios for deploying next-generation 5G communication systems show [3,4] that the 60 GHz frequency band is proposed to be used not only for deploying personal networks WPAN (Wireless Personal Area Network) but also for creating small cells SC (Small Cell), which will make it possible to increase the data transfer rate in the segment of servicing mobile subscribers in the area of dense urban development and to expand the capabilities of the IoT technologies, which require a large number of devices to be connected to a wireless communication channel [5].

Unlike the centimeter wavelength, where 4G wireless networks are currently being introduced [6,7], the use of the millimeter wave band (MM WB) provides higher data transfer rates due to the formation of narrow signal beams, high gain of antennas at their small aperture and increase in the noise immunity of the communication channel. However, a significant disadvantage in this case is a large attenuation of the radio signal in atmospheric gases, hydrometeors and the presence of some other types of additional losses [8, 9].The international organization ITU has developed and proposed recommendations [10, 11] for calculating possible signal attenuation when using modern communication systems in the MM WB in different climatic zones. Additional studies of the local microclimate features and its impact on the deployment efficiency and availability of millimeter-wave band communication channels during long-term operation are being carried out to clarify statistical data [12,13] in many countries, including in the countries of Eastern Europe.

The purpose of the work is to clarify the calculation methodology and assess the availability and performance parameters of communication channels in the millimeter wave band when deploying 5G communication network segments in various climatic zones of Ukraine.

II. Assessment of the Achievable Data Transfer Rates

Figure 1 shows one of the possible scenarios for deploying a *5G* network under a dense urban development conditions.

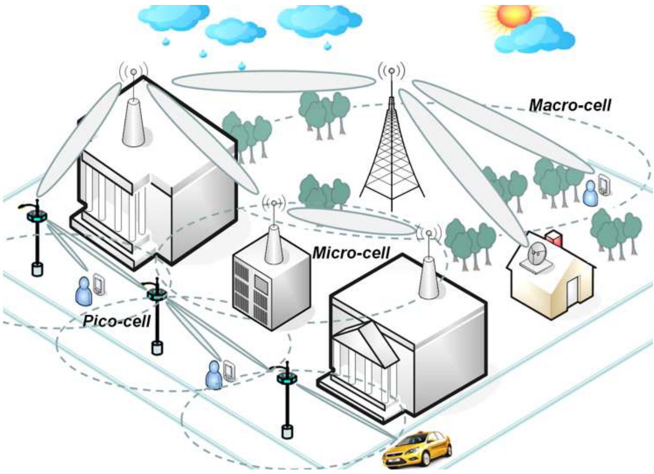

Fig. 1. Scenario of deployment of 5G networks based on small

The unlicensed *60 GHz* band, with a large signal attenuation in the atmosphere, makes it possible to reuse the frequency channels allocated to the provider, and the *MIMO* array technologies for forming narrow beams at base stations (*BSs*) and access points (*APs*) reduce significantly intra-system interference. In this case, the problem of frequency planning for building small cells becomes not so relevant.

The use of the MM WB is also a feature of the scenario, both for building elements of the transport network (*Backhaul link*) and subscriber access lines (*Access link*) for user terminals *D* (*Device*) and *IoT* devices (Fig. 2).

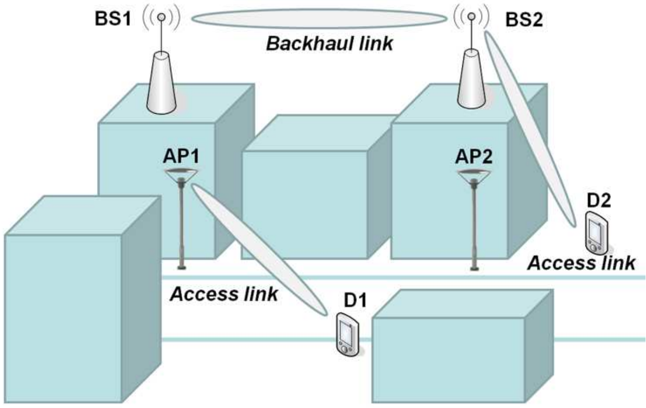

Fig. 2. Main scenarios for using the 60 GHz band for various network segments under conditions of urban development.

60 GHz frequency band is recognized as unlicensed one and its frequency distribution is presented in Table. 1 for different regions and countries of the world [14].

TABLE I. 60 GHz UNLICENSED FREQUENCY BAND

Parameter	Countries and Regions of the World				
	North America	Japan	South Korea	Australia	EU
Frequency range, *GHz*	57-64	59-66	57-64	59,4-62,9	57-64
Channel bandwidth, *GHz*	2,16	2,16	2,16	2,16	2,16
Transmitter power, *dBm*	-	10	10	10	27
Equivalent isotropic power in antenna, *dBm*	40 medium 43 peak	57	57	51,8	40 medium 43 peak

One of the parameters given in Table. 1 shows the equivalent isotropically radiated power in the antenna EIRP (Equivalent Isotropically Radiated Power), which is the integral power characteristic of the transmitter, considering the directional properties of the antenna. Formula (1) shows that a low-power radio transmitter with a directional antenna can emit in a certain direction the same level of radio emission as a high-power radio transmitter with a weakly directional antenna.

$$EIRP = P_{TX} + G_{TX} \qquad [dBm] \tag{1}$$

where: P_{TX} is the transmitter power, *dBm*; G_{TX} is the transmitting antenna amplification factor, *dBi*.

To determine the bandwidth of the communication channel, it is necessary to conduct a detailed estimate of the budget of the radio link length d, taking into account the transmitter power $EIRP$, the attenuation of the *60 GHz* signal along the path $PL(d)$, the attenuation due to the presence of oxygen $O(d)$ in the atmosphere, the influence of precipitation in the form of rain $R(d)$ and the gain of the receiving antenna G_{RX}. The received signal level in the receiver P_{RX} can be represented as:

$$P_{dB}^{RX}(d) = P_{TX} + G_{TX} - PL(d) \\ -O(d) - R(d) + G_{RX}\,[dB] \tag{2}$$

Under conditions of urban development for the radio network segments shown in Fig. 1, two basic models can be used to calculate the *60 GHz* signal attenuation $PL(d)$ along the path: the line-of-sight (*LOS*) model and the street canyon (*Street Canyon*) model [15, 16]:

$$PL(d)_{LOS} = 32,5 + 20\log_{10}(f) \\ +10n\log_{10}(d/1000)[dB] \tag{3}$$

$$PL(d)_{SC} = 82,02 + 10n\log_{10}(d/d_O)\Big|_{do=5}[dB] \tag{4}$$

where: f is the signal frequency in *GHz*; n is the coefficient depending on conditions of signal propagation (2…6) [15]: $n = 2$ for the *LOS* scenario; $n = 3 - 5$ for the *Street Canyon* scenario; d is the distance between transmitting and receiving antennas, *m*; d_0 is the reference distance, $d_0 = 5m$. Table. 2 shows the values of the coefficient n for different propagation conditions.

TABLE II. SHOWS THE VALUES OF THE COEFFICIENT n FOR DIFFERENT PROPAGATION CONDITIONS

Conditions of Propagation	*n*
Free space	2
Open space in the city	2,7-3,5
Space in the densely built city	3-5
Inside LOS buildings	1,76-1,8
Inside NLOS buildings	4-6

When calculating the budget of the MM WB radio link with a length of more than 100 m, it is necessary to consider the attenuation in atmospheric gases (that is, the absorption of O_2 in atmospheric oxygen) and attenuation depending on the precipitation intensity. The absorption level in atmospheric oxygen must be considered on radio paths longer than 400 m and at a frequency of *60 GHz* it is $O(d) = 16dB/km$ [10]. $O(d) = 16 \cdot d/1000\ [dB/m]$ for the distance between the transmitting and receiving antennas in the meter scale. Attenuation factors in rainfall $R(d)$ depend on the rain climate zone, and they are recorded by the International Telecommunication Union (*ITU*) [9]. The territory of Ukraine is in three climatic zones according to the intensity of precipitation (Fig. 3-4). Table. 3 presents the *ITU* data on precipitation rates by climatic zones.

$$R(d) = \gamma_R \cdot d/1000\ [dB/m] \tag{5}$$

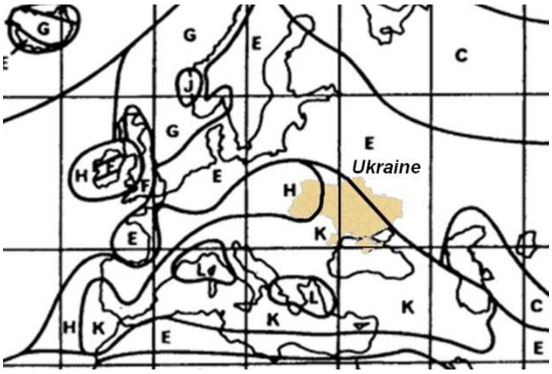

Fig. 3. Location of Ukraine in three climatic zones of the ITU

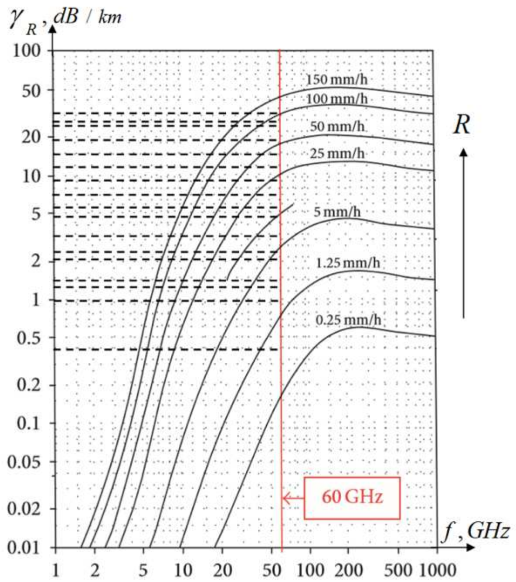

Fig. 4. The dependence of the linear attenuation γ_R on the signal frequency and precipitation intensity *R*

The value of the linear attenuation of the *60 GHz* signal in rain γ_R, depending on the intensity of precipitation *R* [*mm/h*], can be determined using the graphs shown in Fig. 4 [9, 17]. Dotted lines in the graph represent attenuation levels γ_R [*dB km*] in rain.

The intensity of precipitation, the presence of clouds and other local meteorological factors of the atmosphere in the MM WB significantly affect the ability of the communication system to provide the data transfer with specified quality indicators. The availability ratio *AR (availability ratio)* of the communication channel is defined as the ratio of the time when the communication channel is in the available state to the observation period, which, as a rule, is taken equal to one year (365.25 days, 8766 hours). The unavailability ratio *NR (unavailability ratio NR=1-AR)* is defined as the fraction of time during which the path (connection) is in the unavailable state over the observation period. The period of unavailability begins counting from the moment when a sequence of ten seconds occurs with a significant number of errors [14].

Table. 3 shows the numerical values of the rain attenuation levels γ_R for three climatic zones *E* (Kharkov), *H* (Lvov), *K* (Kiev) with different availability ratio (*AR)* of the radio communication line. To complete the formation of the parameters of the radio link budget, let us take the value of the receiving antenna gain G_{RX} equal to the transmitting antenna gain G_{TX}.
Then

$$G_{RX} = G_{TX} = EIRP - P_{TX} = 43 - 27 = 16\left[dBi\right] \quad (6)$$

Expressions (1) - (6) allow calculating the budget of the radio link depending on the distance d_{TX-RX} for different climatic zones, deployment scenarios, and percent of the availability of the *AR* communication line.

TABLE III. SHOWS THE NUMERICAL VALUES OF THE RAIN ATTENUATION LEVELS γ_R FOR THREE CLIMATIC ZONES

Downtime percentage *NR* (%)	**Availability of Line *AR*** (%)	**Precipitation Intensity Data by Climatic Zone and Linear Attenuation at *60 GHz***					
		***E* Zone**		***H* Zone**		***K* Zone**	
		R *mm/h*	γ_R *dB/km*	*R* *mm/h*	γ_R *dB/km*	*R* *mm/h*	γ_R *dB/km*
1,0	99,0	0,6	0,4	2,0	1,2	1,5	1,0
0,3	99,7	2,4	1,4	4,0	2,0	4,2	2,2
0,1	99.9	6,0	3,5	10,0	4,9	12,0	7,0
0,03	99,97	12,0	7,0	18,0	8,0	23,0	9,1
0,01	99,99	22,0	9,0	32,0	12,0	42,0	15,0
0,003	99,997	41,0	14,9	55,0	23,0	70,0	26,0
0,001	99,999	70,0	26,0	83,0	29,0	100,0	32,0

The limiting bandwidth of the communication channel, depending on the distance d_{TX-RX} between the transmitter and the receiver, the bandwidth, and the signal-to-noise ratio, can be estimated based on the Shannon formula [20]:

$$C(d) = BW_{60GHz} \cdot \log_2\left(1 + \frac{P_W^{RX}(d)}{N_W}\right)\left[Bit/s\right] \quad (7)$$

where: *BW* is the bandwidth in *Hz* for *60 GHz* band ($BW = 2.16 \cdot 10^9\, Hz$); $P_W^{RX}(d)$ is the power of the received signal at the input of the receiver in *W* at a distance from the transmitter ($P_W^{RX}(d) = 10^{(P_{dB}^{RX}(d)/10)}$);$N_W$is the noise power in *W* $N_W = 10^{(N_{dB}/10)}$ .The noise power *N* depends on various factors: the frequency range, the bandwidth of the radio communication channel and the noise of the implementation of a specific communication system of the *IEEE 802.11ad* standard [20, 21].

$$N_{dB} = k_B T_c + 10\log_{10}(BW_{60GHz}) + L_I + n_F\left[dB\right] \quad (8)$$

where: $k_B T_e$ is the noise power spectral density ($k_B T_e = -174\ dB/Hz$) ; *BW* is the bandwidth in *Hz* for *60 GHz* band; L_1 is the attenuation during the implementation of *IEEE 802.11ad* standard equipment $\left(L_I = 10\ dB\right)$; $n_F$is the noise factor of the *IEEE 802.11ad* standard equipment ($n_F = 5\ dB$) . Then for the communication equipment of the *IEEE 802.11ad* standard we get $N_{dB} = -65.6555\left[dB\right]$ and $N_W = 2.72 \cdot 10^{-10}\left[W\right]$.

Figures 5 and 6 show the dependences of the maximum data transmission rate on the length of the *60 GHz* radio link of the communication system in the point-to-point mode (*Backhaul link*) and in the subscriber access mode (*Access link*) for three climatic zones of Ukraine.

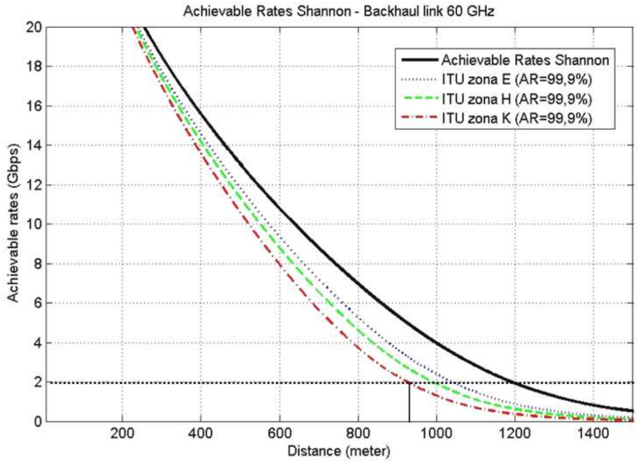

Fig. 5. Location of Ukraine in three climatic zones of the ITU

If we take *2 Gbit/s* as the limiting minimum data transfer rate over the communication channel (this transfer rate is necessary for broadcasting video in real time), then one can determine the maximum radius of the service area for base stations (*Backhaul link*) and mobile network subscribers (*Access link*) depending on the climatic zone of Ukraine.

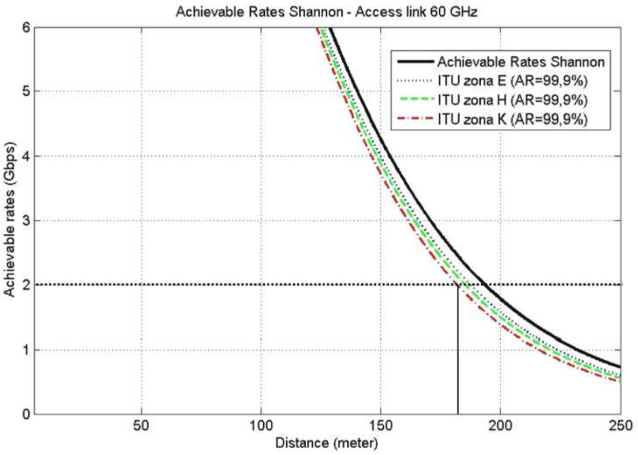

Fig. 6. Location of Ukraine in three climatic zones of the ITU

The radius of action for micro-cells (*Micro-Cell*): 950 *m* (K zone); 1000 *m* (H zone) and 1050 *m* (E zone). The radius of action for pico-cells *(Pico-Cell)*: *180 m* (K zone); *185 m* (H zone) and *190 m* (E zone). To estimate the real bandwidth of the communication channel based on existing systems, it is necessary to refer to the *IEEE 802.11ad* standard [21], which indicates the recommended modulation schemes MCS_i *(Modulation and Coding Scheme*) for three main modes of equipment operation: using one *SC (Single carrier)*, orthogonal frequency-division multiplexing *OFDM* and low-power mode *LPSC (Low-Power SC).* For each of the modes of operation, the standard proposes different modulation indices, the values of the receiver sensitivity P_{RX}^{MCSi} and the maximum achievable data transfer rate *DR (Data rate).* Table. 4 shows the data on the sensitivity of the receiver for the mode of operation using a single carrier (*SC)* [21]. This mode is mandatory for all equipment manufacturers.

TABLE IV. SHOWS THE DATA ON THE SENSITIVITY OF THE RECEIVER FOR THE MODE OF OPERATION USING A SINGLE CARRIER (SC)

MCS_i Circuit for *SC* Mode	Sensitivity of Receiver *RX* P_{RX}^{MCSi}, *dBm*	Type of Modulation	Code Rate	Data Transfer Rate *DR, Mbit/s*
MCS0	-78 dBm	DBPSK	3/4	27,500
MCS1	-68 dBm	π/2 BPSK	1/2	385,00
MCS2	-66 dBm	π/2 BPSK	1/2	770,00
MCS3	-65 dBm	π/2 BPSK	5/8	962,50
MCS4	-64 dBm	π/2 BPSK	3/4	1155,00
MCS5	-62 dBm	π/2 BPSK	13/16	1251.25
MCS6	-63 dBm	π/2 QPSK	1/2	1540.00
MCS7	-62 dBm	π/2 QPSK	5/8	1925.00
MCS8	-61 dBm	π/2 QPSK	3/4	2310,00
MCS9	-59 dBm	π/2 QPSK	7/8	2502,50
MCS10	-55 dBm	π/2 16QAM	1/2	3080,00
MCS11	-54 dBm	π/2 16QAM	5/8	3850,00
MCS12	-53 dBm	π/2 16QAM	3/4	4620,00

If the calculated power of the received signal P_{dB}^{RX} is higher than the sensitivity of the receiver $P_{RX}^{MCS_i}$ with the modulation index MCS_i and lower than the sensitivity of the receiver P_{RX}^{MCSi+1} with the modulation index MCS_{i+1}, then the processor of the *IEEE 802.11ad* radio modem sets the modulation index *MCSi*.

$$P_{RX}^{MCSi} < P_{dB}^{RX}(d) \le P_{RX}^{MCSi+1} \left[dBm \right] \tag{9}$$

Therefore, if the distance of the wireless link increases, then $P_{dB}^{RX}(d)$ becomes lower due to signal attenuation (i.e., loss in the propagation medium, oxygen, and rain), then the index of the supported *MCSi* also becomes lower and this leads to a decrease in the data transfer rate over the radio communication channel.

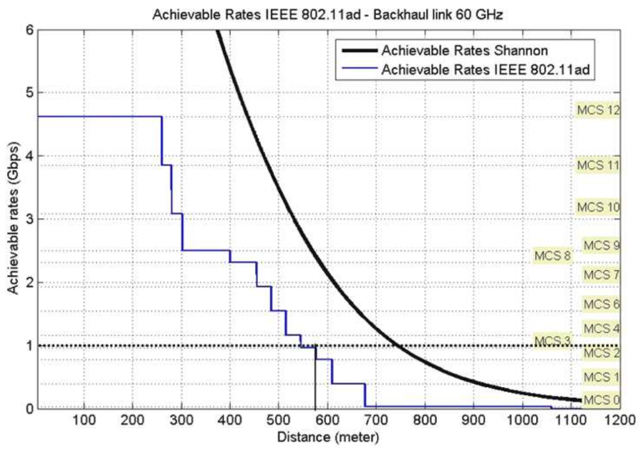

Fig. 7. Dependence of the data transfer rate on the length of the radio link of the communication system of the IEEE 802.11ad 60 GHz standard in the point-to-point mode (Backhaul link)

The specific value of the switching thresholds P_{RX}^{MCSi} depends on the objective function of the adaptation algorithm of the radio communication system: maintaining a constant transmitter power at the base station, maintaining the maximum data transfer rate, or maintaining the required quality of the communication channel.

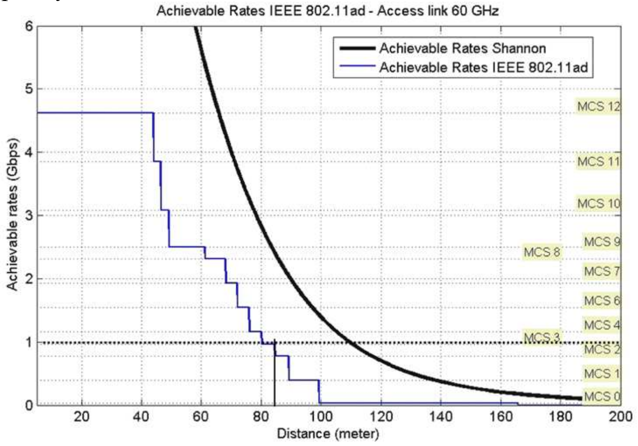

Fig. 8. Dependence of the data transfer rate on the length of the radio link of the communication system of the *IEEE 802.11ad 60 GHz* standard in the subscriber access mode (*Access link*)

Figures 7 and 8 show the dependences of the data transfer rate on the length of the radio link of the *IEEE 802.11ad 60 GHz* communication system in the point-to-point mode (*Backhaul link*) and in the subscriber access mode (*Access link*). If we take *1 Gbit/s* of the *IEEE 802.11ad 60 GHz* standard of the communication system as the limiting minimum data transfer rate over the communication channel, then we can determine the maximum radius of the service area for base stations and mobile network subscribers. The radius of action for the micro honeycomb cells will be 600 *m*; and the radius of action for pico-honeycomb cells will be 85 *m*.

III. Conclusions

1. Nowadays, the number of mobile users has grown significantly, and they want more reliable service and faster data transfer rates. *5G* networks in the millimeter wave band can provide a higher data transfer rate.
2. The transmission of the MM WB signals above *10 GHz* is vulnerable to precipitation. Rain, snow, sleet, ice particles, and hail can attenuate and scatter microwave signals and therefore reduce availability in terms of the system quality.
3. In this work, a model and results of an assessment of the communication link budget are presented, based on which the achievable distances between the transmitter and the receiver for various climatic zones of Ukraine are determined.
4. This work provides a theoretical assessment of the achievable data transfer rates based on the communication channel capacity according to Shannon, and an assessment of the practically achievable data transfer rates for various segments of the data transfer network for the equipment of the *IEEE 802.11ad* standard, using various modulation and coding schemes (*MCS*).

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