Channel Capacity of High Altitude Platform Systems: A Case Study

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Abstract: This paper presents a model for Multiple-Input Multiple-Output (MIMO) Land High Altitude Platform channels and analytical evaluation of Discrete-input Continuous-output Memoryless Channel capacity for High Altitude Platform (HAP)–MIMO systems, where practical transmission environments are considered. Furthermore, for HAP– Single-Input Single-Output (SISO) systems, we propose an adaptive transmission mechanism relying on the transmit power characterized by value at the transmitter side. Achievable channel capacity bounds are established for both idealized and realistic adaptive coding schemes with well-adopted modulation types, namely Phase Shift Keying and Quadrature Amplitude Modulation.

Keywords: *High altitude platform, adaptive coded modulation, M-ary phase shift keying, M-ary quadrature amplitude modulation, channel capacity.*

I. Introduction

High Altitude Platform (HAP) broadband communication networks have been increasingly playing an important role in supporting broadband wireless communication systems, namely fourth generation Long Term Evolution (4G-LTE) and fifth generation (5G) networks [1]. HAPs are communication facilities situated at an altitude of 17 to 30 km and at a particular point relative to the Earth [2]. These platforms are mostly solar-powered, unmanned and remotely operated. They have the capability of carrying diverse relay payload supporting multi-purpose communications. In addition, they could be in the form of full base station or, in some cases, a simple transponder, which is similar to the configuration used in satellite communication systems [2]. HAPs in a fully deployed configuration are capable of providing services and applications ranging from broadband wireless access, navigation and positioning systems, remote sensing and weather observation/monitoring systems, mobile telephony as well as digital television [3].

Due to low-cost implementation, HAPs are expected to become a popular solution for the wireless communications infrastructure [4]. In 2014, two large companies, Google and Facebook, announced their investments in HAP related projects, aiming to provide internet access in the regions where communications infrastructures based on terrestrial or satellite transmissions are not available [5]. Multiple-Input Multiple-Output (MIMO) transmission promises a significant increase in the system capacity and availability of communication links in a multipath propagation environment. It is an extension of diversity principles often applied in wireless links to improve link reliability. Combining the transmit and receive diversity results in a new concept, which not only increases the link reliability but also offers a potential increase for the radio link capacity. The challenge nowadays is to investigate the application of MIMO techniques to the Land High Altitude Platform (LHAP) communication. Some models using multiple HAP constellations have shown that capacity can be significantly increased by using highly directional user antennas to spatially discriminate between HAPs in different parts of sky [6].

The single links in HAP systems over wireless channels typically experiences the fading and other time varying propagation losses. In such channels, adaptive transmission schemes may be employed for achieving the highest throughput possible [7]. The main idea is to adapt transmission parameters of modulation schemes and of error-control codes, in accordance to variations of the transmission channel. Adaptation strategies in [8–10] assumed that perfect channel-state information (CSI) is readily available at the transmitter or at the receiver. Other adaptive schemes considered the employment of pilot or training symbols, in order to estimate the channel state information [11]. In contrast, more practical adaptation schemes were proposed in [12] and [7], where statistics derived from the demodulator and decoder at the receiver may be used for providing inputs to the adaptive mechanisms. These schemes are capable of supporting nearly optimal performance, when dispensing the requirement of full-duplex transmission or the use of pilot symbols.

As a reflection of these trends, different aspects of the channel capacity of HAP based systems were analysed in [13], where the Continuous-Input Continuous-Output Memoryless Channel (CCMC) capacity of HAP based systems were investigated for the additive white Gaussian noise (AWGN) channel in different path loss scenarios.

As compared to the above-mentioned studies and extensive research in [14] that focuses on channel capacity of HAP-Single-Input Single-Output (SISO) systems, the original contributions of this paper are as follows. First, we first clarify a framework of the HAP based systems, where we focus on characterizing the fading channel model, where the effects of both fast fading and slow fading are taken into consideration along with different pathloss scenarios. Second, we compute the Discrete-input Continuous-output Memoryless Channel (DCMC) capacity for HAP-MIMO for benchmarking the design of HAP based systems employing specific coherent modulation schemes. Third, we present an analytical evaluation of channel capacity bounds for HAP-SISO links invoking adaptive coded modulation schemes in realistic channel conditions and establishing achievable channel capacity bounds for both idealized and realistic adaptive coding schemes associated with both popular modulation types, namely Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM). We also propose the adaptive mechanism relying on the transmit power ratio transmitted from the transmitter to the noise power encountered at the receiver.

The rest of the paper is organized as follows. In Section II, a review of the HAP propagation channel model is provided. In Section III, the channel capacity associated with the HAP-MIMO employing different modulation schemes is described. In Section IV, the adaptive channel capacity for the HAP-SISO links is derived for the corresponding adaptive coded modulation mechanisms. Finally, our conclusions are given in Section V.

II. HAP Propagation Channel Model

From the system architecture point of view, HAP communication system can be used in different configurations. In the simplest configuration HAPs are used as standalone platforms, providing broadband wireless access to terminals located in their coverage area. In the case of multi-platform constellation, HAPs can be interconnected via ground stations or by inter-platform links (IPL) forming a network of HAPs, thus arbitrarily extending the system coverage.

Furthermore, a HAP system can be deployed as a standalone network or it can be connected to external networks via gateways providing suitable interworking functionality.

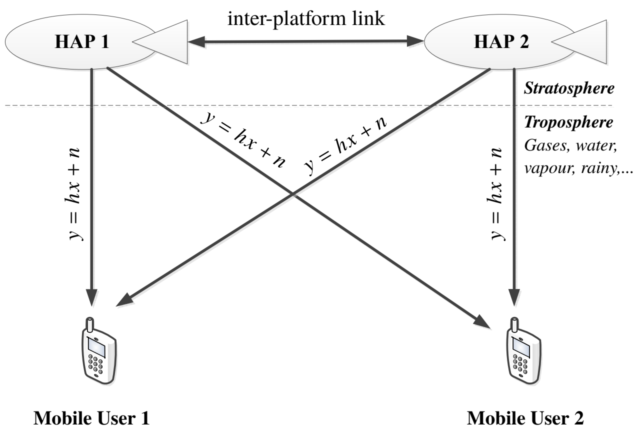

Figure 1. Channel model for HAP operating environment.

In order to investigate also the potential gain offered by exploiting space and platform diversity, we consider a configuration with two HAPs and two mobile users (MUs) (Figure 1). The principle of diversity is to provide two or more statistically independent channels for transmission of the same information. In the case of space diversity, independent channels are provided by receiving the same signal using multiple antennas suitably separated in space. Due to limited availability of space, weight and power for the communication payload on the platform, space diversity in the sky segment can only be achieved by transmitting the same signal from multiple platforms.

From the perspective of space and platform diversity, the HAP system architecture enables four operating scenarios: (i) single HAP-single MU (SISO), (ii) single HAP-two MUs (Single-Input Multiple-Output: SIMO), (iii) two HAPs-single MU (Multiple-Input Single-Output: MISO), and (iv) two HAPs-two MUs (MIMO).

As seen in Figure 1, transmission links in the HAP system are affected by various influences of the propagation environment such as free space loss, attenuation due to meteorological effects and multipath fading. Let us now consider a single transmission link in the HAP system of Figure 1 associated with the transmitted and received signals of x and y, respectively. It should be noted that x and y are two complex numbers representing a symbol transmitted and received in the context of the single transmission link, respectively. Accordingly, the received signal can be represented as

$$y = hx + n \tag{1}$$

where $h = Ah_s h_f$ is the complex-valued fading coefficient that comprises three components. The first component, A, is the path loss, which includes free space loss and attenuations associated with above-mentioned weather scenarios.

The second component, h_s, is the block fading coefficient, which is also known as slow fading, large-scale shadow fading or quasi-static fading, which may be deemed to be unchanged for all symbols within a frame duration. The third component, h_f, is the fast fading or small-scale fading, which fluctuates on a symbol-by-symbol basis. Finally, n is the AWGN process having a variance of $N_0/2$ per dimension, where N_0 is the power spectral density of the noise.

Considering the frequency of $f = 28$ GHz and $f = 30$ GHz typically used in an Asian region, Table I lists magnitudes of path loss that subject to the free space loss and attenuation pertaining to different weather conditions occurring on the single transmission link, when measured at an elevation angle of $\theta = 12°$, a temperature of $t° = 7°$C, the water vapour concentration of $\rho = 6$ g/m^3, the absolute humidity of 10 g/m^3 and the average rain density of 0.01%/year [13].

Values of the path loss A may be calculated as

$$A = A_{\text{fs}} + A_{\text{a}}, \tag{2}$$

where A_{fs} is the free-space loss and A_{a} is the atmospheric attenuation due to influences of the clear air, fog, cloud as well as rain at Ka-band frequencies that depends on weather conditions: clear-sky, $A_{\text{a\_cs}}$ (in dB), or rainy, $A_{\text{a\_r}}$ (in dB).

Expressing the free space loss A_{fs} in dB, with frequency f in MHz and distance from HAP to user r in km, depending on elevation angle, θ (*i.e.*, $r = h_{\text{HAP}}/\sin\theta$, where h_{HAP} is the platform height in km), we obtain

$$A_{\text{fs}} = 32.4 + 20\log r + 20\log f. \tag{3}$$

In order to assess the channel capacity degradation due to atmosphere, the total equivalent conditionally fading is required. Establishing the total equivalent conditionally fading is somewhat more complicated. We have calculated the attenuation due to atmosphere for different weather conditions, by combining the attenuations due to influences of the clear air, mixed cloud and rain. Thus, the atmospheric attenuation in clear sky condition $A_{\text{a\_cs}}$ in dB may be calculated as

$$A_{\text{a\_cs}} = A_{\text{w}} + A_{\text{o}}, \tag{4}$$

where A_{w} is the attenuation due to water vapor, and A_{o} is the attenuation due to oxygen.

Similarly, the atmospheric attenuation in rainy condition $A_{\text{a\_r(dB)}}$ in dB may be computed as

$$A_{\text{a\_r}} = A_{\text{w}} + A_{\text{o}} + A_{\text{cloud}} + A_{\text{rain0.01\%}}, \tag{5}$$

where A_{cloud} is the attenuation due to mixed cloud, and $A_{\text{rain0.01\%}}$ is the attenuation due to rain exceeded for 0.01% of an year. Details on computing these attenuation can be refer to [13].

TABLE I
PATHLOSS MAGNITUDE OF THE SINGLE TRANSMISSION LINK IN DIFFERENT WEATHER CONDITIONS

Pathloss (dB)	f = 28 GHz	f = 31 GHz
Clear-Sky	157.4020 dB	158.5402 dB
Rainy	200.9416 dB	206.8696 dB

III. DCMC CHANNEL CAPACITY FOR HAP-MIMO SYSTEMS

When a fixed modulation scheme is activated in the HAP system, the associated DCMC capacity may be achieved by invoking an idealized channel coding scheme [15]. Without loss of generality, let us assume that the information transmitted over the channel has uniform distribution. By employing the classic Monte Carlo simulation method for averaging the expectation terms, the DCMC capacity in BPS of the transmission link may be calculated as [16]:

$$C_{(\eta)}^{\text{DCMC}}(R) = \eta - \frac{1}{M}\sum_{l=1}^{M} E\left[\log_2 \sum_{z=1}^{M} \exp\left(\psi_{l,z}\right)\Big|_{X_l}\right], \tag{6}$$

where R is the information rate, $M = 2^\eta$ is the number of modulation levels, while η is the number of modulated bits and $E[A|X_l]$ is the expectation of A conditioned on the M-ary signals X_l. More specically, Equation (6) represents the capacity of the MIMO DCMC that can be reached when employing a channel code such as Space Time Block Code (STBC) [17].

Note that $\psi_{l,z}$ is a function of both the transmitted signal and of the channel as defined in [16, Equation (21)]. For the system relying on a single transmit and a single receiver antenna, we have

$$\psi_{l,z} = \frac{-\left|h(x_l - x_z) + n\right|^2 + |n|^2}{N_0}. \tag{7}$$

Let us define the faded signal to noise power ratio at the transmitter side as $\text{SNR}_t = E\left[\frac{1}{|h|^2}\,\text{SNR}_r\right]$, where SNR_r is the faded signal to noise power ratio at the receiver side. Following the approach in [18, 19], where N_0, is assumed to be constant, then on average we have

$$\text{SNR}_t = \text{SNR}_r + A. \tag{8}$$

At a given information rate R, we readily identify the corresponding signal to noise power ratio $\text{SNR}_t|_R$. So $\text{SNR}_t|_R$ is defined as the SNR_t value associated with the capacity $C_{(\eta)}^{\text{DCMC}} = R$ on the $C_{(\eta)}^{\text{DCMC}}$-versus-SNR_t capacity curve represented by Equation (6) and plotted in Figure 2, where an information rate of R may be maintained.

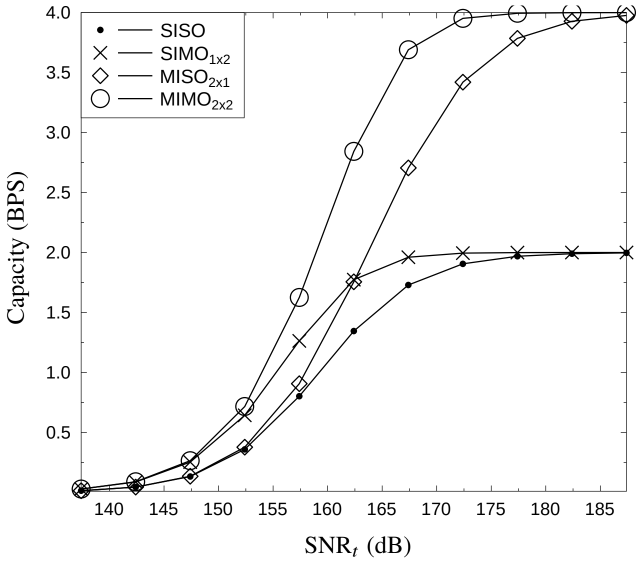

Figure 2. Capacity curves of the DCMC calculated by Equation (6) for the above four operating scenarios HAP-MIMO experiencing uncorrelated Rayleigh (fast or small-scale) fading channel, when employing QPSK in clear-sky at frequency of f = 28 GHz.

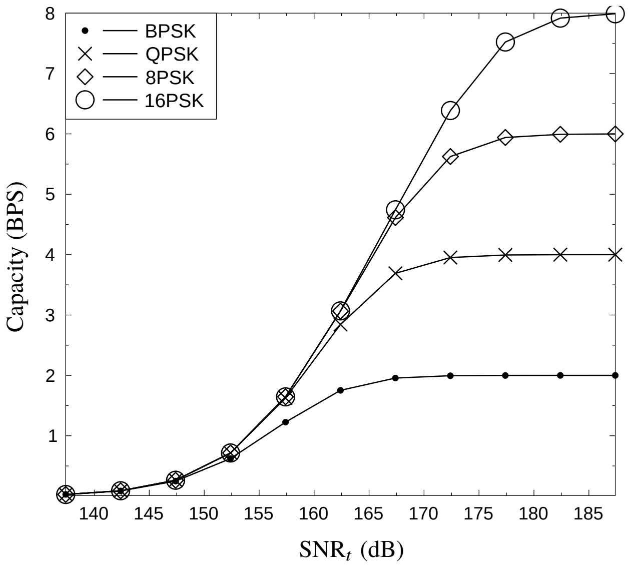

Figure 3. Capacity curves of the DCMC calculated by Equation (6) for a HAP-MIMO$_{2\times2}$ experiencing uncorrelated Rayleigh (fast or small-scale) fading channel, when employing M-ary PSK in clear-sky at frequency of f = 28 GHz.

As a direct result of having formulated the DCMC capacity for the HAP transmission link presented in Figure 2 and Figure 3, one may roughly predict the differences in the performance of transmission link in HAP systems. For example, depending on the value of SNR$_t$ given at the transmitter reflecting the transmit power, the HAP system may provide infinitesimally low Bit Error Rate/Frame Error Rate (BER/FER) performance. Additionally, if SNR$_t$ value is given, the transmitter may decide the most beneficial modulation scheme that should be activated, as seen in Figure 2 and Figure 3.

In HAP-MIMO system if any one path is faded, there is a high probability that the other paths are not, so the signal still gets through. The channel capacity of a MIMO antenna system can be improved without using additional transmit power and spectral bandwidth over SISO antenna system. Specifically in Figure 2, the channel capacity in HAP-MIMO$_{2\times2}$ increased by 2 times compared to HAP-SISO system when employing QPSK modulation scheme. Consequently, MIMO is an IEEE 802.11n standard for worldwide [20]. However, MIMO systems are more costly and more complex. Therefore, depending on the requirements of the system design, the choice of antenna configuration (MIMO, MISO, SIMO or SISO) and modulation scheme is appropriate.

Moreover, the SNR$_t$ value determined for a given scenario may be used for determining the maximum gain that may be obtained by further optimizing a given system. The principle of how to calculate the maximum gain was illustrated in [21], where that principle can be further developed for applying into existing systems of [22].

IV. Adaptive Coded Modulation Channel Capacity for the HAP Transmission Link

We consider a downlink transmission between HAP and MU. At the time i, the transmitter sends signal $x[i]$ via LHAP channel that is affected by fading coefficient $h[i]$ and AWGN noise $n[i]$. The receiver is capable of calculating the channel quality based on the outputs of demodulation or decoding, as seen in Figure 4. This information reflecting the channel quality experienced by the system may be used for supporting adaptive mechanisms, which facilitate the transmitter to select appropriate transmission parameters applied for the next frames. Important transmission parameters that can be adapted are the rate of the error correction code and the modulation level, as listed in Table II.

Let the set of error-control codes available at the transmitter be denoted by $\{R_{c_l}, 1 \le i \le N_c\}$, where N_c is the number of coding rates that can be activated by both transmitter and receiver. The set of modulation schemes available at the transmitter is denoted by $\{\eta_j(\text{in BPS}), 1 \le j \le N_m\}$, where N_m is the number of bits per symbol pertaining to the modulation scheme. The information rate R (or the rate of coded modulation schemes) available at both the transmitter and receiver may be represented by $R_\nu = R_{c_l}\eta_j$, where we have $1 \le \nu \le N_cN_m$. Accordingly, there may be two main

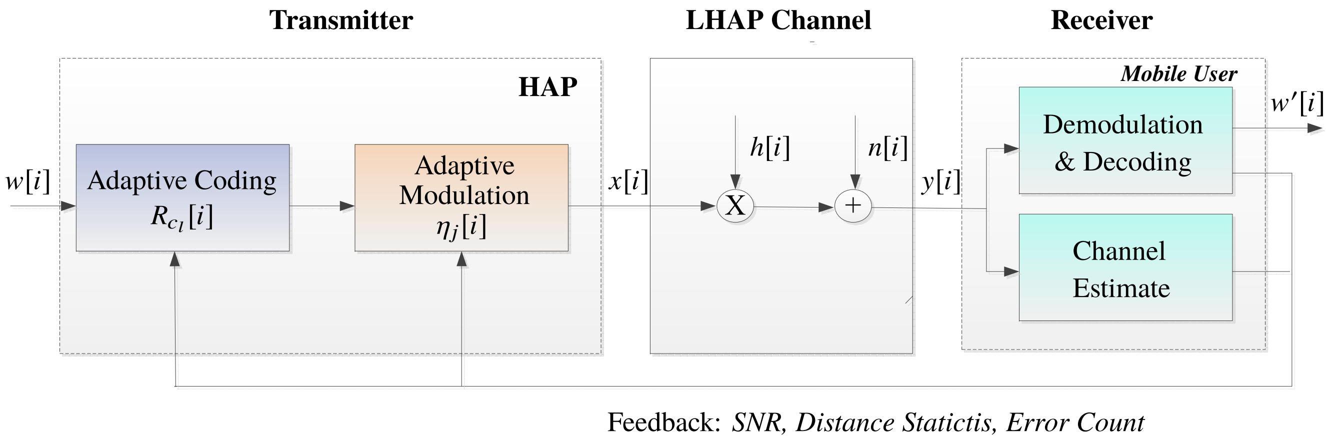

Figure 4. Adaptive coded modulation principle.

TABLE II
SNR_t INTERVALS, CODE RATE R_c AND INFORMATION RATE R, WHEN APPLYING THE ADAPTATION MECHANISM RELYING ON M-ARY PSK MODULATION SCHEMES FOR HAP-TO-GROUND TRANSMISSION OVER RAYLEIGH FADING CHANNEL AT f = 28 GHZ IN A CLEAR-SKY CONDITION.

SNR_t **intervals** (dB)	**Mod. scheme**	**Code rate,** R_c	**Information rate,** R (BPS)
[137.4, 147.4)	BPSK	0.01 to 0.12	0.01 to 0.12
	4QAM	0.005 to 0.18	0.15 to 0.36
[147.4, 157.4)	QPSK	0.07 to 0.4	0.12 to 0.8
	8QAM	0.12 to 0.28	0.36 to 0.8
[157.4, 162.4)	8PSK	0.27 to 0.5	0.8 to 1.51
	16QAM	0.2 to 0.42	0.8 to 1.66
[162.4, 167.4)	16PSK	0.38 to 0.58	1.51 to 2.33
	32QAM	0.3 to 0.55	1.66 to 2.74
≥ 167.4	32PSK	≥0.5	≥2.33
	64QAM	≥ 0.45	≥ 2.74

approaches for optimizing the transmission performance, namely transmit power per information bit [7] and channel capacity [23]. However, we only concentrate on the second approach here.

As seen in Figure 4, the measurement of channel quality statistics is carried out at the receiver, in order to provide feedback information to the transmitter. Based on the feedback information, the beneficial modulation scheme is activated for the transmission of the next frame.

To illustrate the principle, we use SNR_t as the indicator of the channel quality. Accordingly, the SNR_t intervals shown in Table II may be employed for selecting the beneficial modulation scheme that allows the system to transmit at the highest information rate possible. It should be noted that in order to approach the capacity both adaptive coding and modulation have to be activated. As a result, we have the modulation scheme, SNR_t intervals, the coding rate R_c and the ultimate information rate R detailed in Table II.

Moreover, it was proved that the channel capacity corresponding to the idealized channel coding may be approached when a highly complex decoder is affordable at the transmitter [24]. To strike the trade-off between complexity and near-capacity performance, the realistic coding schemes of [21] may be used for providing an arbitrary coding rate R_c and an infinitesimally low BER at the SNR_t value that is d = 0.5 dB away from the corresponding channel capacity.

Accordingly, given a transmit power represented by SNR_t value, the maximum channel capacity C may be calculated based on the corresponding curves plotted in Figures 5 and 6. Concerning the maximum channel capacity, the most beneficial modulation scheme and the associated channel coding rate can also be determined. Ultimately, the results for both well-adopted modulation types, M-ary PSK and M-ary QAM, are presented in Table II. As a result, we have the channel capacity for the HAP transmission link employing adaptive coding and modulation scheme plotted in Figures 5 and 6 for both modulation categories over the entire SNR_t range of our interest. It should be noted that there is a gap of 0.5 dB between channel capacity in the scenario of invoking an idealised channel coding scheme and a realistic channel coding scheme, as seen in Figures 5 and 6.

V. CONCLUSIONS

In this paper, we have presented the results of analytical evaluation of channel capacity for HAP-MIMO systems

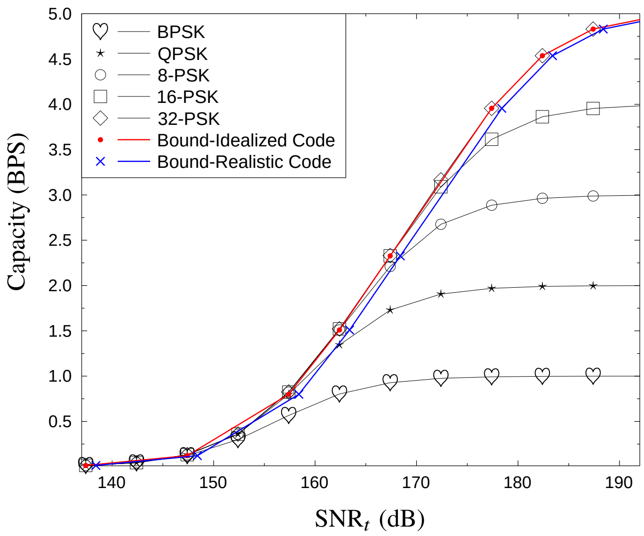

Figure 5. DCMC capacity bound for the M-ary PSK adaptive transmission schemes in HAP-SISO system over Rayleigh fading channel in clear-sky at frequency of f = 28 GHz.

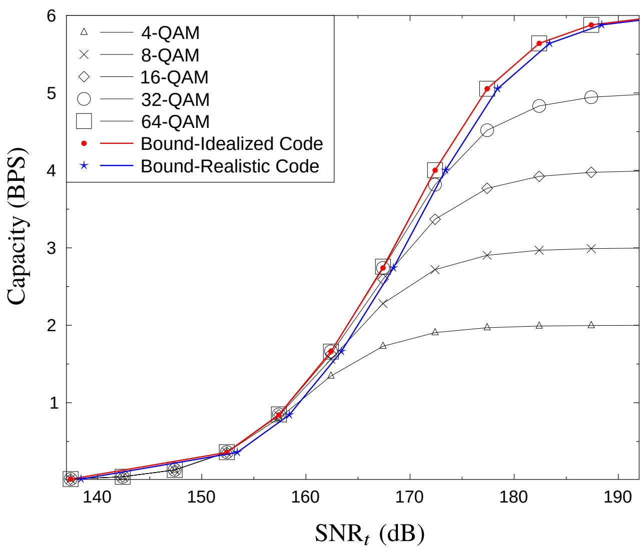

Figure 6. DCMC capacity bound for the M-ary QAM adaptive transmission schemes in HAP-SISO system over Rayleigh fading channel in clear-sky at f = 28 GHz.

employing specific modulation schemes at Ka-band frequencies under practical transmission environment. From these results, we found that MIMO techniques improved significantly on system capacity and availability of communication links. Moreover, the success of MIMO techniques integration into commercial standards, such as 3G, 4G, WiMAX, WLAN and LTE, also shows that implementation of MIMO in HAP communication systems is feasible. More specifically, we derived the achievable capacity bounds for both idealized and realistic adaptive coded modulation schemes in HAP-SISO systems, when the transmit power is pre-determined for well-adopted modulation types, namely M-ary PSK and M-ary QAM. As a further investigation, our proposed bounds on channel capacity of the HAP-SISO systems using adaptive coded modulation schemes could be adopted for assessing the performance of receivers designed for LHAP transmission links.

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