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Research Article

Capacity of 60 GHz Wireless Communications Based on QAM

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With apparent advantages of the several GHz license-free spectrums, 10 W maximum transmit power, and so forth, 60 GHz wireless communication technology has become the first choice for Gbps level short-range wireless communications. This paper researches 60 GHz wireless communications over the additive white Gaussian noise channel. Channel capacity with quadrature amplitude modulation (QAM) is investigated for the unlicensed 59–64 GHz radio spectrum set aside by FCC. Moreover, the capacity with QAM is compared to that with phase shift keying (PSK). It is shown that QAM is capable of providing Gbps data rate and outperforms PSK especially when the modulation order is large. The results prove that QAM is an attractive scheme for 60 GHz wireless communications.

1. Introduction

The growth of wireless communications is spurred by the consumer desire for untethered access to information and entertainment. While contemporary unlicensed systems support light and moderate levels of wireless data traffic, as seen in Bluetooth and wireless local area networks (WLANs), current technology is unable to supply data rates comparable to wired standards like gigabit Ethernet and High-Definition Multimedia Interface (HDMI) [1]. An abundance of unlicensed spectrum surrounding the 60 GHz operating frequency has the ability to support these high-rate communications.

The 60 GHz band is an excellent choice for high-speed Internet, data, and voice communications since it offers benefits such as several GHz license-free spectrums, 10 W maximum transmit power, virtually interference-free operation, high level of frequency reuse enabled, and highly secure operation [2]. However, the 60 G wireless channel shows 20 to 40 dB increased free space path loss and suffers from 15 (up to 30) dB/km atmospheric absorption depending on the atmospheric conditions. Multipath effects, except for indoor reflections, are vastly reduced at 60 G making non-line-of-sight (NLOS) communication very difficult [1, 3]. While the high path loss seems to be disadvantage at 60 GHz, it, however, confines the 60 GHz operation to within a room in an indoor environment. Hence, the effective interference levels for 60 GHz are less severe than those systems located in the congested 2–2.5 GHz and 5–5.8 GHz regions [2]. The oxygen absorption also enables higher "frequency reuse" since radiation from one particular 60 GHz radio link is quickly reduced to a level that will not interfere with other 60 GHz links operating in the same geographic vicinity [3]. Federal Communications Commission (FCC) set aside the 59–64 GHz frequency band for general unlicensed applications [4]. The effect of the antenna directionality to 60 GHz channel capacity is studied in [5]. The throughput of wireless mobile ad hoc networks with directional antennas at 60 GHz unlicensed band is investigated in [6]. The capacity analysis of 60 GHz wireless communications based on PSK modulation is given in [7, 8]. Quadrature amplitude modulation (QAM) is widely used for the high-speed data transmission [9–11].

Compared with other digital modulation techniques like PSK or PAM, QAM modulation has better anti-noise performance and could make full use of the bandwidth.

In this paper, we investigate the capacity of 60 GHz wireless communication system over AGWN channel under the FCC rules. The major modulation method used here is QAM, and capacity comparison between QAM and PSK is also simply illustrated. The rest of the paper is organized as follows. Section 2 presents the general used QAM constellations and makes a comparison between two different constellations for 8-QAM. Section 3 calculates channel capacity over AWGN channel in 60 GHz wireless communication system. Section 4 conducts Monte Carlo simulations to illustrate the channel capacity. And Section 5 gives a conclusion.

2. QAM Constellations

QAM can be viewed as combined amplitude and phase modulation. When the requirement of data transfer rate exceeds the upper limit 8-PSK can provide, QAM is generally used. Because the QAM constellation points are much more disperse than PSK constellation points and the distances between the constellation points are much bigger with the same ary. So QAM modulation could provide a better transmission performance.

QAM signal waveforms may be expressed as [10]

$$S_m(t) = A_{mc}g(t)\cos 2\pi f_c t - A_{ms}g(t)\sin 2\pi f_c t, \quad (1)$$

where A_{mc} and A_{ms} are the information-bearing signal amplitudes of the quadrature carriers and $g(t)$ is the signal pulse. The vector representation of these waveforms is

$$S_m = \left[A_{mc}\sqrt{\frac{1}{2}\varepsilon_g} \quad A_{ms}\sqrt{\frac{1}{2}\varepsilon_g} \right], \quad (2)$$

where ε_g is the energy of the basic signal pulse $g(t)$.

M-QAM constellations can be constructed in many different ways, and they have different capacity and error characteristics. Although rectangular, circle, and star signal constellations are common in practice, a certain kind of constellation can be designed to achieve the best communication performance, under some specific premises [12, 13].

Figures 1 and 2 present two 8-QAM constellations. Figure 1 is a rectangular 8-QAM constellation and Figure 2 is a circular 8-QAM constellation.

Assuming that the signal points are equally probable, the average transmitted signal power is [4]

$$P_{av} = \frac{1}{M}\sum_{m=1}^{M}\left(A_{mc}^2 + A_{ms}^2\right) = \frac{A^2}{M}\sum_{m=1}^{M}\left(a_{mc}^2 + a_{ms}^2\right), \quad (3)$$

where (a_{mc}, a_{ms}) are the coordinates of the signal points, normalized by A.

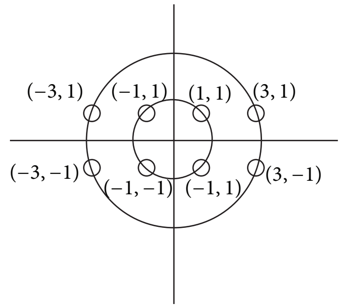

Figure 1: Rectangular 8-QAM constellation.

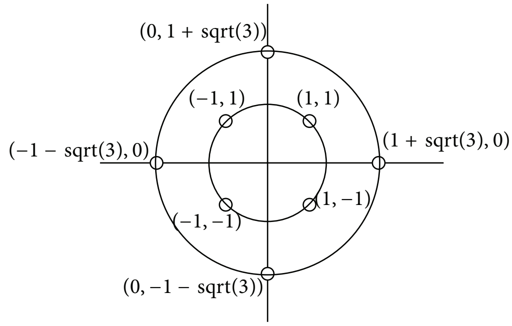

Figure 2: Circle 8-QAM constellation.

As can be seen from the above figures, the minimum distances between the constellation points for (a) and (b) are, respectively,

$$d_a = 2\sqrt{\frac{1}{6}}, \qquad d_b = 2\sqrt{\frac{1}{3+\sqrt{3}}}. \quad (4)$$

Comparing both,

$$\text{Ratio} = \frac{d_b}{d_a} = \sqrt{\frac{6}{3+\sqrt{3}}} \approx 1.126, \qquad \text{Ratio}_{\text{dB}} = 20\log(1.126) \approx 1.03. \quad (5)$$

Minimum distance of signal set shown in Figure 1 is approximately 1 dB less than that shown in Figure 4 with the same average transmitted power. The more the distance between the constellations, the less the chance of a constellation point getting decoded incorrectly. Actually, the second signal constellation is the optimal one for 8-QAM because it has the largest minimum Euclidean distance between signal points for a given transmitted power. At the same time, as shown in Figure 5, signal set with the circle constellation for 8-QAM provides a higher data rate.

Rectangular QAM signal constellations have distinct advantage of being easily generated and transmitted as two PAM signals impressed on phase-quadrature carriers. In addition, they are easily demodulated. Although, it is

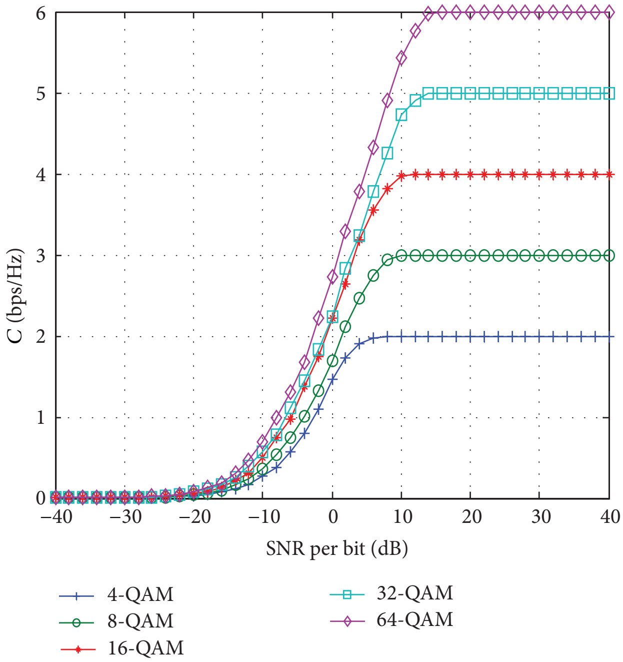

Figure 3: Channel capacity of M-ary QAM system over AGWN channels.

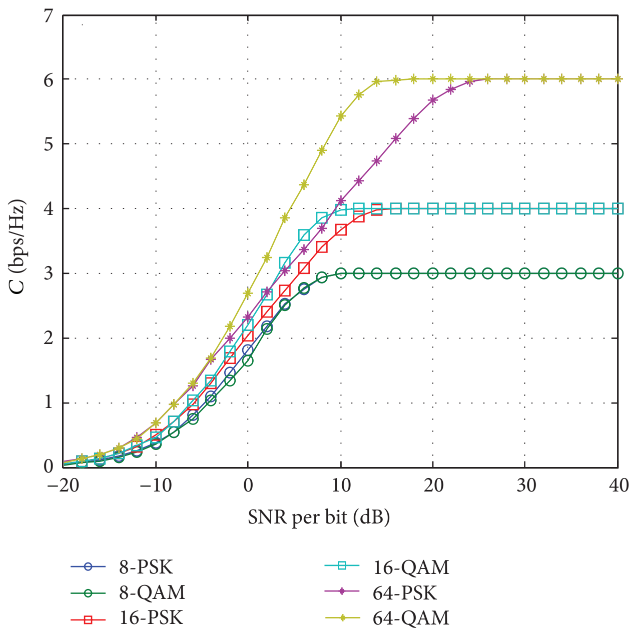

Figure 4: Relations between capacities of M-ary PSK and QAM with the same average power.

generally a sub-optimal modulation scheme, compared to other M-QAM constellations, in the sense that they do not maximally space the constellation points for a given energy. For $M \geq 16$, the minimum distance required to achieve a given average transmitted power is only slightly smaller than the minimum distance required for the optimal M-ary

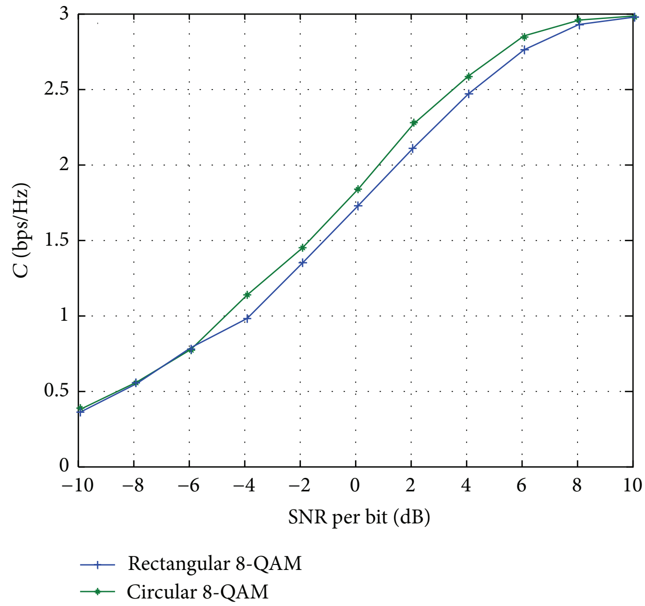

Figure 5: Capacity comparison between two different 8-QAM signal constellations.

QAM signal constellation. For these reasons, rectangular M-ary QAM signals are most frequently used in practice [10]. And they are also adopted in this paper.

3. Channel Capacity

In general, the channel capacity is a function of the channel realization, transmitted signal power and noise. For AWGN channel, the shannon capacity is normalized with respect to the bandwidth and expressed in bps, that is, normalized with respect to the bandwidth, is

$$C = W\log_2(1 + \text{SNR}), \tag{6}$$

where W is the system band width and SNR is the receive signal to noise ratio, defined by ε_b/N_0, where ε_b is the energy per bit [9].

The Shannon capacity predicts the channel capacity C for an AWGN channel with continuous-valued inputs and outputs. However, a channel employing multilevel/phase modulation, for example, PAM, PSK, or QAM modulation, has discrete-valued inputs and continuous-valued outputs, which impose an additional constraint on the capacity calculation [10].

We consider the modulation channels with discrete-input X and continuous-output Y, which is defined as [7, 9]

$$Y = X + W, \tag{7}$$

where W is a zero-mean Gaussian random variable with variance σ^2 and $X = x_k$, $k = 0, \ldots, q-1$. For a given X, it follows that Y is Gaussian with mean x_k and variance σ^2. That is,

$$p\left(\frac{y}{x_k}\right) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(y-x_k)^2/2\sigma^2}. \tag{8}$$

The capacity of this channel in bits per channel use is the maximum average mutual information between the discrete input $X = \{x_0, x_1, \ldots, x_{q-1}\}$ and the output $Y = \{-\infty, \infty\}$. That is,

$$C = \max_{p(x_i)} \sum_{i=0}^{q-1} \int_{-\infty}^{\infty} p(y \mid x_i) p(x_i) \log_2 \frac{p(y \mid x_i)}{p(y)} dy, \quad (9)$$

where

$$p(y) = \sum_{k=0}^{q-1} p(y \mid x_k) p(x_k). \quad (10)$$

Assuming an equal a priori probability real or complex signal constellation, that is, $p(x_i) = 1/q$, the channel capacity of an AWGN channel with q-ary modulation is then [10]

$$\begin{aligned} C &= \log_2(q) - \frac{1}{q}\sum_{k=0}^{q-1} \mathbf{E}_{y|x_k} \left\{ \log_2 \frac{\sum_{i=0}^{q-1} p(y \mid x_i)}{p(y \mid x_k)} \right\} \\ &= \log_2(q) \\ &\quad - \frac{1}{q}\sum_{k=0}^{q-1} \mathbf{E}_{y|x_k} \left\{ \log_2 \sum_{i=0}^{q-1} \exp\left[-\frac{\left|x_k + w - x_i\right|^2 - |w|^2}{2\sigma^2} \right] \right\}, \end{aligned} \quad (11)$$

where E[·] is the expected value operator and w is the complex white Gaussian noise, modeled as a Gaussian distributed random variable with zero mean and variance σ^2 in each real dimension. Equation (11) is a universal formula applied to q-ary PAM/PSK/QAM and can be evaluated by Monte Carlo simulation. With normalized signal energy, the relationships between channel capacity and SNR can be evaluated by (11).

4. Experimental Results and Analysis

In this paper, Monte Carlo simulations are conducted to present the channel capacity of 60 GHz over AWGN channels under FCC regulations.

Figure 3 shows the normalized channel capacity for M-ary QAM system over AGWN channels. It is shown that the achievable data rate is 8.42 Gbps for a 60 GHz with 5 GHz bandwidth at a SNR of 0 dB for 8-QAM system. And for 16-QAM and 64-QAM, the data rate can be 11.14 Gbps and 13.19 Gbps. Hence QAM has potential to support Gbps data transmission in the 60 GHz system.

Figure 4 shows comparison of channel capacities for M-ary PSK and QAM systems with the same average transmitted power. It shows that the data rate for M-QAM is higher than that for M-PSK, especially when $M > 8$. For 16-QAM, the data rate can improve 6.8% at a SNR of 0 dB and for 64-QAM the improvement can reach 14.1%. That is to say, QAM can achieve a higher data rate even at a lower SNR. We can conclude from this figure that when $M > 8$, capacity performance of the QAM system is better than that of the PSK system. The superiority of QAM is obvious because it has the largest minimum Euclidean distance between signal points for a given transmitted power.

Figure 5 demonstrates the difference among channel capacities for different M-QAM constellations. It shows that, for 8-QAM, the circle constellation provides a higher data rate. This confirms our analysis in Section 2. Moreover, the capacity advantage of QAM with circle constellation over that with rectangular constellation is quite small, whereas the latter is much easier to implement in practice. Hence rectangular QAM modulation is more preferable for 60 GHz wireless communications.

5. Conclusions

PSK is the common used modulation for 60 GHz currently, because of its advantages in bandwidth and SNR. However, the data rate for M-PSK is obviously lower than that of M-QAM, with the same average transmitted power. Moreover, as M increases, the distance between the adjacent phases gradually decreases, which reduces the noise tolerance and makes it difficult to guarantee the error rate, while QAM can improve the noise tolerance and provide a lower error rate.

For M-QAM, many different signal constellations can be designed and conducted, from which we can select an optimal one to meet our specific requirements in 60 GHz wireless communication.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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