Capacity of 60 GHz Wireless Communication Systems over Fading Channels

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***Abstract*—This paper considers the channel capacity of 60GHz wireless communications systems over Rayleigh fading channels and Ricean fading channels. The SNR and therefore capacity varies according to the communication distance. The capacity is presented for line-of-sight (LOS) and non-line-of-sight (NLOS) channels given based on a 60GHz link budget model. Phase shift keying (PSK) modulation is considered under FCC power constraints for the unlicensed 59-64GHz radio spectrum. The channel capacity over Rayleigh fading channels is compared with the capacity in additive white Gaussian noise channels. The paper also investigates the channel capacity of 60GHz wireless communications systems over Ricean fading channels and gives the channel capacity compariasion with q-ary PSK modulation over Ricean fading channel, AWGN channel and Rayleigh channel when the SNR per symbol is given. The results show that a 60GHz wireless system is more suitable for short range communications less than 100 meters rather than long distances.**

***Index Terms*—Channel capacity, AWGN, Rayleigh fading, Ricean fading, 60GHz**

I. Introduction

The desire for unrestricted access to information and in particular multimedia spurs the growth of wireless communications. However, the lower frequency spectrum is almost completely occupied. Fortunately, an abundance of widely available spectrum around 60 gigahertz (GHz) is available to support high-rate, unlicensed wireless communications. The up to 7 GHz of bandwidth is very suitable for short-range wireless communication, and is an excellent prospect for future system development.

The regulations and standards of each country are slightly different according to IEEE 802.15.3c [1][2][3][4][5]. In 2001, the United States Federal Communications Commission (FCC) set aside 7 GHz of contiguous spectrum between 57 and 64 GHz for unlicensed use. In 2000, the Ministry of Public Management, Home Affairs, Posts, and Telecommunications (MPHPT) of Japan issued 60 GHz radio regulations for unlicensed utilization in the 59–66 GHz band [2]. The 54.25–59 GHz band is, however, allocated for licensed use. The maximum transmit power in the unlicensed band is limited to 10 dBm with a maximum allowable antenna gain of 47 dBi. Unlike in North America, Japanese regulations specify that the maximum transmission bandwidth must not exceed 2.5 GHz. There is no specification for RF radiation exposure and transmitter identification requirements. In Europe, point-to-point fixed services in the 64–66 GHz band is recommended. Figure 1 shows the international unlicensed spectrum around 60GHz [1][2].

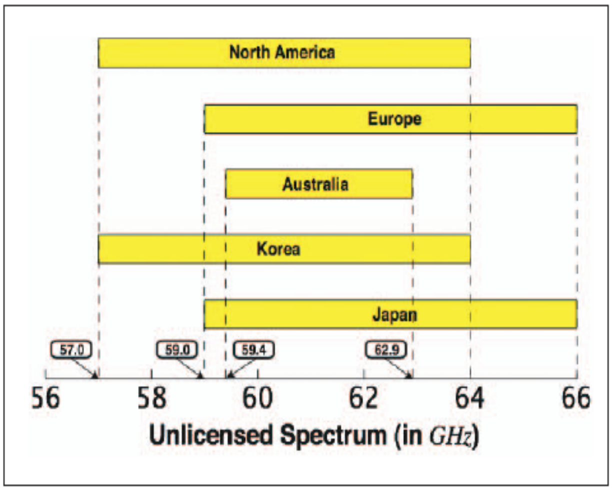

Figure 1. International unlicensed spectrum around 60 GHz.

With 7 GHz of bandwidth, 2-3Gbit/s high definition media interface (HDMI) or wireless gigabit Ethernet could be achieved even using simple modulation methods, for example, PAM, PSK and QAM. Furthermore, 60 GHz regulations allow for a much higher transmit power (10W) compared to existing wireless local area network (WLAN) and wireless personal area

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network (WPAN) systems. The higher transmit power is necessary to overcome the higher path loss at 60 GHz.

60 GHz wireless systems present several challenges that have made deployment difficult [2][3][4]. The 60 GHz channel has 20 to 40 dB increased free space path loss compared to lower frequency bands, and suffers from 15 to 30 dB/km of atmospheric absorption depending on the conditions. In addition, multipath effects are vastly reduced at 60 GHz making non-line-of-sight (NLOS) communications very difficult. Furthermore, increased phase noise, limited amplifier gain, and the need for transmission line modeling of circuit components due to the ultra high frequencies [2][3][4][5] are challenges for millimeter-wave transceivers.

IBM engineers have reported the development of 60 GHz front-end chip sets [2][5], and the first experimental 60 GHz transmitter and receiver chips using a high-speed alloy of silicon and germanium (SiGe). Meanwhile, researchers from UCLA, UC Berkeley Wireless Research Center (BWRC), and other universities and institutes are using widely available and inexpensive complementary metal oxide semiconductor (CMOS) technology to build 60 GHz transceiver components.

To date, there have been few results on the channel capacity of these systems. The capacity of a 60 GHz wireless communication system over an AWGN channel was presented in [6]. However, Rayleigh fading channels and Ricean fading channels are more practical, especial in non-line-of-sight (NLOS) and part line-of-sight (LOS) environments. This paper investigates the capacity of 60 GHz systems over Rayleigh fading channels and Ricean fading channels considering the FCC transmission rules.

The rest of the paper is organized as follows. Section II presents the 60GHz link budget model and Shannon capacity. The channel capacity over Rayleigh fading channels and Ricean fading channels is calculated in Section III, and results to illustrate the capacity are given in Section IV. Finally, Section V concludes the paper.

II. 60G LINK BUDGET MODEL AND SHANNON CAPACITY

A. 60GHz Link Budget Models

In 2001, the FCC set aside 7 GHz of spectrum between 57 and 64 GHz for wireless communications. Their rules limit the equivalent isotropic radiated power in this band to a maximum power density of 9 μW/cm^2 at 3 meters from the radiating source [7]. This means that 40 dBm transmit power is the legal power limit with an antenna having 0 dBi gain.

The link budget model according to Friis free-space path loss formula is

$$P_r = P_t + G_t + G_r - P_L \qquad (1)$$

where Pt is the transmit power, Pr is the received power at distance d, Gt and Gr are antenna gain for the transmit and receive antennas respectively, both assumed to be 0 dB for simplicity. All expressions are in decibels (dB). It is shown in [8] that the received signal strength is dominated by the distance from the transmitter and the receiver, taking into account the oxygen absorption. The general path loss model can be expressed as

$$P_L(dB) = 10\log_{10}\left(\frac{4\pi d}{\lambda}\right)^n \qquad (2)$$

where λ is the wavelength corresponding to the center frequency fc, n is the path loss exponent which can be approximated as 1.55 for line-of-sight (LOS) channels and 2.44 for non-line-of-sight (NLOS) in an indoor home environment (5-15m) [10]. In conference room environments, n can be approximated as 1.77 in line-of-sight (LOS) channels and 3.85 in non-line-of-sight (NLOS) environments [11]. Using the frequency range from 57 to 64 GHz, the constraint on the transmit power is

$$Pt \le 40dBm \qquad (3)$$

If thermal noise as the primary source of interference, the required sensitivity at the receiver can be calculated as

$$S_r = NF + F + SNR \qquad (4)$$

where NF is the noise floor calculated by thermal noise

$$N = kTWF \qquad (5)$$

F is the noise figure (optimistically) assumed to be 0 dB, SNR is the signal to noise ratio at the receiver, k is Boltzmann's constant, and T is the room temperature (typically 290K). For the 60 GHz system, the noise floor is calculated as -76 dBm. To ensure adequate performance at the receiver, the minimum received power should be greater than or equal to the required sensitivity. Thus the relationship between the system performance and maximum communication distance can be derived as

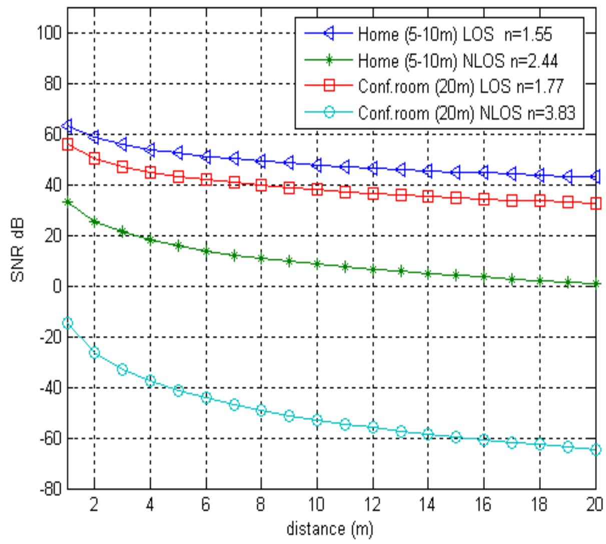

Figure 2. Received SNR versus communication distance for a 60GHz wireless system over LOS and NLOS channels and employing the FCC in band power density limit.

$$SNR \le 116 - 10\log_{10}\left(\frac{4\pi d}{\lambda}\right)^n \quad (6)$$

The relationship between SNR and distance is shown in Fig. 2. This shows that there is about 20dB in attenuation in LOS environments in both the home (5-15m) and conference room (20m) environments. However, in NLOS channels, the SNR degradation as distance increases is very significant, especially in conference room environments.

B. Shannon Capacity

Channel capacity can be calculated according to the Shannon capacity [12] which is given by

$$C = W\log(1+SNR) \quad (7)$$

where W is the system bandwidth, SNR is the receive signal to noise ratio, defined as Eb/N0, where Eb is the energy per bit and N0 is the noise power spectral density. The relationship between the capacity and communication distance is then given by

$$C \le W\log_2(1+10^{(116-10\log_{10}(\frac{4\pi d}{\lambda})^n)/10}) \quad (8)$$

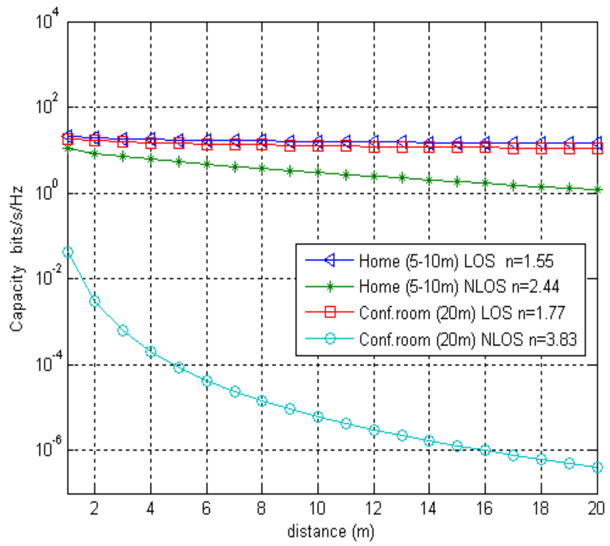

Figure 3. The achievable Shannon capacity versus communication distance.

Figure 3 shows the Shannon capacity limit for the LOS and NLOS cases. It can be observed that there is only a small capacity decrease for the LOS cases (n=1.55 and n=1.77), while the operating distance for the NLOS n=3.83 case is limited to several meters because the capacity decreases drastically as a function of distance. To improve the capacity, we can either increase the bandwidth or signal-to-noise ratio (SNR), or both. According to (1), improving the transmit antenna gain Gt and/or the receive antenna gain Gr can also improve the capacity.

III. 60 GHZ CHANNEL CAPACITY OVER RAYLEIGH AND RICEAN FADING CHANNELS

A. Channel Capacity with PSK Modulation over AWGN Channels

The Shannon capacity expression (7) corresponds to 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 imposes an additional constraint on the capacity calculation. We consider modulation channels with discrete-inputs and continuous-outputs, which was capacity given in [12] as

$$C = \max_{P(x_i)} \sum_{k=0}^{q-1} \int_{-\infty}^{\infty} p(y|x_k)P(x_k)\log_2 \frac{p(y|x_k)}{p(y)}dy \quad (9)$$

where

$$p(y) = \sum_{i=0}^{q-1} p(y|x_i)P(x_i) \quad (10)$$

xk is the discrete-valued input, and y is the continuous-valued output, modeled as

$$y(t) = x(t) + w(t) \quad (11)$$

where w(t) is additive white Gaussian noise (AWGN) with variance N0/2 in each dimension.

Assuming an equal a priori probability real or complex signal constellation, i.e. $P(x_i) = 1/q$, the channel capacity of an AWGN channel with q-ary modulation is then [6][13]

$$\begin{aligned} C &= \log_2(q) - \frac{1}{q}\sum_{k=0}^{q-1} \mathbf{E}_{y|x_k}\left\{\log_2 \frac{\sum_{i=0}^{q-1} p(y|x_i)}{p(y|x_k)}\right\} \\ &= \log_2(q) - \frac{1}{q}\sum_{k=0}^{q-1} \mathbf{E}_{y|x_k}\left\{\log_2 \sum_{i=0}^{q-1} \exp\left[-\frac{|x_k+w-x_i|^2-|w|^2}{2\sigma^2}\right]\right\} \end{aligned} \quad (12)$$

where E[.] denotes expectation, w is complex white Gaussian noise, modeled as a Gaussian distributed random variable with zero mean and variance σ^2 in each real dimension. Equation (12) can be evaluated by Monte Carlo simulation. Note that (12) is a universal formula which applies to q-ary PAM/PSK/QAM, although PSK is commonly used in 60 GHz systems. With normalized signal energy, the relationship between channel capacity and SNR can be evaluated using (12), as well as the relationship between channel capacity and communication range.

B. Channel Capacity with PSK Modulation over Rayleigh and Ricean Fading Channels

On wireless channels, channel capacity is typically degraded by fading phenomena which arise from multipath propagation. In NLOS cases, the channel can be modeled using a Rayleigh distribution. While in most cases, there are LOS paths and NLOS paths, so the channel can be modeled using a Ricean distribution. The complex process received at the output of a noisy flat-fading wireless channel is then

$$y(t) = h(t)x(t) + w(t) \qquad (13)$$

where h(t) is a generally time-correlated ergodic fading complex sequence independent of x(t) and w(t), and w(t) is complex zero mean AWGN with variance N0/2 in each dimension. Assuming coherent detection at the receiver, the effect of fading is reduced to multiplication of the transmitted symbol x(t) by the real nonnegative random variable h(t), which represents the envelope of the complex fading. Therefore, without loss of generality, we can rewrite (13) in an equivalent sampled form.

$$y(n) = h(n)x(n) + w(n) \qquad (14)$$

With perfect channel state information available at the receiver, it is known that the capacity of the channel in (14) can be directly obtained by averaging the corresponding conditional capacity $\tilde{C}(h)$ with respect to the probability density function (pdf) of the fading gain. This leads to the following expression for the channel capacity of fading channels for an equiprobable signal constellation

$$C = \int_0^{\infty} \tilde{C}(h)p(h)dh \qquad (15)$$

where

$$\tilde{C}(h) = log_2(q) - \frac{1}{q}\sum_{k=0}^{q-1} E_{y|x_k}\left\{ log_2 \sum_{i=0}^{q-1} exp\left[-\frac{|y-hx_i|^2 - |y-hx_k|^2}{2\sigma^2} \right] \right\} \qquad (16)$$

With Rayleigh fading, h can be modeled as a complex Gaussian variable with zero mean and variance σ^2 in each dimension. Rayleigh fading model assumes that all paths are NLOS paths and there is no a dominant path.

While for Ricean fading, h can be modeled as a complex Gaussian variable with means m for the real and imaginary parts, and variance σ^2 in each dimension. The Ricean parameter is defined as $\beta = \frac{m^2}{\sigma^2}$ which means the ratio of the LOS paths power to the NLOS paths power.

Ⅳ. NUMERICAL RESULTS

Monte Carlo simulation was used to evaluate the channel capacity of a 60 GHz communication system over Rayleigh fading channels under FCC restrictions. These results are compared with the AWGN channel capacity.

To provide a basis for comparison, Fig. 4 gives the normalized channel capacity of q-ary PSK modulation over an AWGN channel [6]. This shows that the achievable data rate for BPSK is 3.75 Gbps with 5 GHz bandwidth and an SNR of 0 dB.

The normalized channel capacity of q-ary PSK over Rayleigh fading channels is shown in Fig. 5. This shows that the achievable data rate for BPSK is about 2.9 Gbps with 5GHz bandwidth at an SNR of 0 dB. Thus there is a significant capacity decease due to the fading.

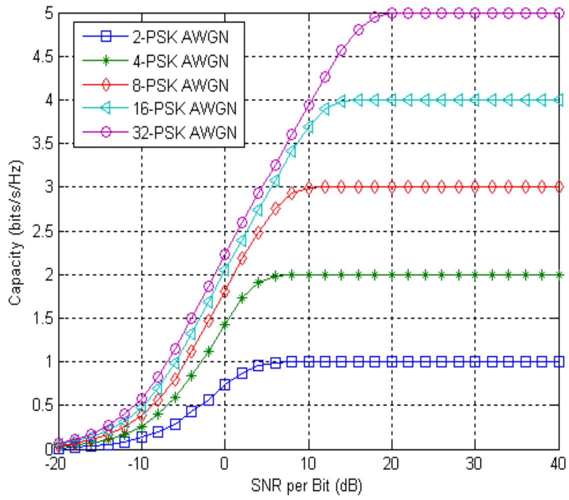

Figure 4. Channel capacity with q-ary PSK modulation over an AWGN channel.

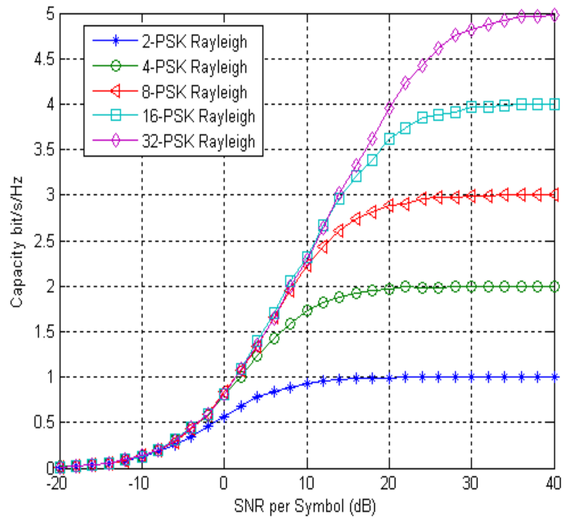

Figure 5. Channel capacity of q-ary PSK over Rayleigh fading channels.

A comparison of q-ary PSK capacity over AWGN and Rayleigh fading channels is given in Fig. 6. As expected, there is no significant difference in the capacities when the SNR is less than 5dB, since the noise dominates performance. However, for values of SNR from 5dB to 20 dB, the capacity decease due to the fading is obvious. In addition, the capacity decease over Rayleigh fading channels is greater as q increases.

The channel capacity of a 60 GHz communication system over Ricean fading channels under FCC restrictions is simulated below. These results are compared with the AWGN channel and the Rayleigh fading channel capacity.

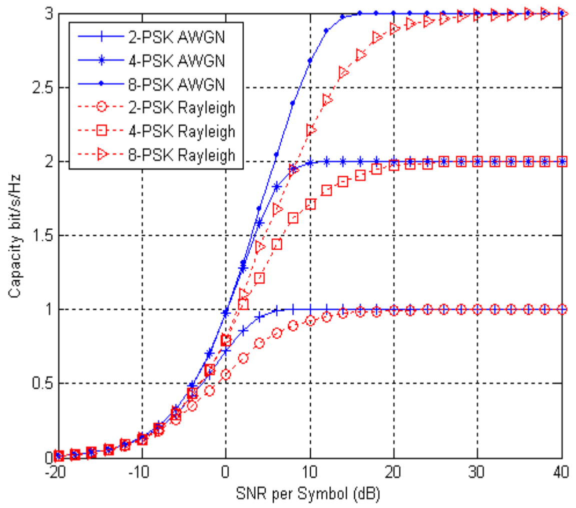

Figure 6. Comparison of q-ary PSK channel capacity over AWGN and Rayleigh fading channels.

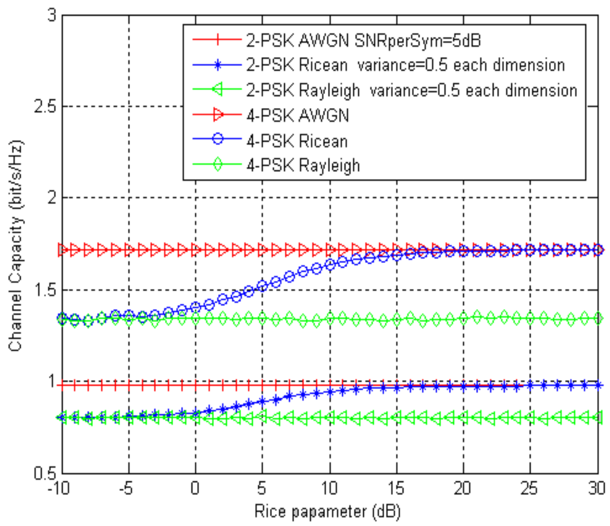

Figure 7. Channel capacity compariasion with q-ary PSK modulation over Ricean fading channel, AWGN channel and Rayleigh channel when the SNR per symbol is 5 dB.

To provide a basis for comparison, Fig. 7 gives the normalized channel capacity of q-ary PSK modulation over Ricean fading channel, AWGN channel and Rayleigh channel when the SNR per symbol is 5 dB. This shows that the achievable data rate for BPSK and 4PSK is increasing with the Ricean parameter increasing.

Fig. 8 gives the normalized channel capacity of q-ary PSK modulation over Ricean fading channel, AWGN channel and Rayleigh channel when the SNR per symbol is 10 dB. Fig. 2 shows that the achievable data rate for BPSK and 4PSK is increasing with the Ricean parameter too. But the increasing of channel capacity when the SNR per symbol is 5 dB is more clearly compared to the SNR per symbol with 10 dB.

Fig.7 and Fig.8 show that when the Ricean parameter is small, for example, less than -5dB, the channel capacity over Ricean fading channel is near to the channel capacity over Rayleigh fading channel because there is much more NLOS paths than LOS paths when the Ricean parameter is small. On the contrary, when the Ricean parameter is big, for example, bigger than 15dB, the channel capacity over Ricean fading channel is near to the channel capacity over AWGN channel because there is much more LOS paths than NLOS paths when the Ricean parameter is big.

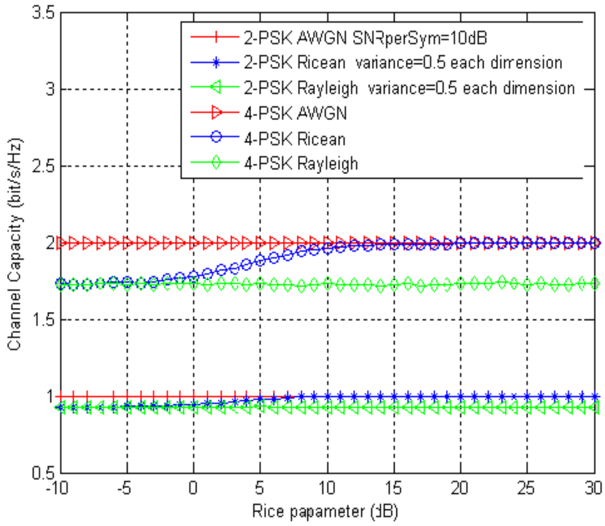

Figure 8. Channel capacity compariasion with q-ary PSK modulation over Ricean fading channel, AWGN channel and Rayleigh channel when the SNR per symbol is 10 dB.

Ⅴ. CONCLUSIONS

The capacity of 60GHz wireless communications over Rayleigh fading channels and Ricean fading channels was investigated for PSK modulation employing FCC in band power density limits. In NLOS cases, the channel can be modeled using a Rayleigh distribution. While in most cases, there are LOS paths and NLOS paths, so the channel can be modeled using a Ricean distribution.

The relationship between channel capacity and SNR or communication range was demonstrated over Rayleigh fading channels in different channel conditions. As expected, the lower the path loss exponent, the longer the communication range. It can be concluded that a 60GHz wireless system is more suitable for short range communications less than 1 km rather than long distances. The q-ary PSK channel capacity over Rayleigh fading channels was shown to be less than the capacity in AWGN channels, particularly in the 5-20 dB SNR range. The capacity decease over Rayleigh fading channels is more serious with increasing q. The relationship between channel capacity and Ricean parameter was demonstrated in different SNR conditions. As expected, the bigger the Ricean parameter, the greater the channel capacity.

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REFERENCES

[1] F. Giannetti, M. Luise, and R. Reggiannini, "Mobile and personal communications in 60 GHz band: A survey," Wirelesss Personal Comun., vol. 10, pp. 207–243, 1999.

[2] S.K. Yong and C.-C. Chong, "An overview of multigigabit wireless through millimeter wave technology: Potentials and technical challenges," EURASIP J. on Wireless Commun. and Networking, vol. 2007, 2007.

[3] C. Doan, S. Emami, D. Sobel, A. Niknejad, and R. Brodersen, "Design considerations for 60 GHz CMOS radios," IEEE Commun. Mag., vol. 42, no. 12, pp. 132–140, Dec. 2004.

[4] M. Karkkainen, M. Varonen, P. Kangaslahti, and K. Halonen, "Integrated amplifier circuits for 60 GHz broadband telecommunication," Analog Integrated Circuits and Signal Processing, vol. 42, pp. 37–46, 2005.

[5] N. Guo, R.C. Qiu, S.S. Mo, and K. Takahashi, "60 GHz millimeter-wave radio: Principle, technology, and new results," EURASIP J. on Wireless Commun. and Networking, vol. 2007, 2007.

[6] H. Zhang and T.A. Gulliver, "On capacity of 60 GHz wireless communications over AWGN channels," Proc. Canadian Conf. on Electrical and Computer Eng., pp. 936-939, May 2009.

[7] ERC Recommendation 12-09, "Radio Frequency Channel Arrangement for Fixed Service Systems Operating in the Band 57.0 - 59.0 GHz which do not Require Frequency Planning, The Hague 1998 Revised Stockholm", Oct. 2004.

[8] N.D. Hawkins, R. Steele, D.C. Rickard, and C.R. Shepherd, "Path loss characteristics of 60 GHz transmissions", Elect. Lett., vol. 21, no. 22, pp. 1054 – 1055, Oct. 1985.

[9] Federal Communications Commission, "Amendment of Parts 2, 15 and 97 of the Commission's Rules to Permit Use of Radio Frequencies Above 40 GHz for New Radio Applications", FCC 95-499, ET Docket No. 94-124, RM-8308, Dec. 1995. Available via: ftp://ftp.fcc.gov./pub/Bureaus/Engineering_Technology/ Orders /1995/fcc95499.txt

[10] M. K. Simon and M. S. Alouini, Digital Communication over Fading Channels, 2nd Ed., Wiley-IEEE Press, New York, NY, USA, 2004.

[11] M. Fiacoo and S. Saunders, Final report for OFCOM - Indoor Propagation Factors at 17GHz and 60GHz, Aug. 1998.

[12] J.G. Proakis, "Digital Communications," 4th Ed., McGraw-Hill, 2001.

[13] H. Zhang and T.A. Gulliver, "Capacity and error probability analysis for orthogonal space-time block codes over fading channels," IEEE Trans. Wireless Commun., vol. 4, no. 2, pp. 808-819, Mar. 2005.

[14] P. Pagani, I. Siaud, N. Malhouroux, W. Li, "Adaptation of the France Telecom 60 GHz channel model to the TG3c framework," IEEE 802.15-06-0218-00-003c, April 2006.

[15] M. Fiacco, M. Parks, H. Radi and S. R. Saunders, "Final Report: Indoor Propagation Factors at 17 and 60GHz," Tech. report and study carried out on behalf of the Radiocommunications Agency, University of Surrey, Aug. 1998.

[16] C. R. Anderson and T.S. Rappaport, "In-Building Wideband Partition Loss Measurements at 2.5 and 60 GHz." IEEE Trans. Wireless Comm. vol. 3, no. 3, pp. 922-928, May 2004.

[17] A. Bohdanowicz, "Wideband Indoor and Outdoor Radio Channel Measurements at 17 GHz" UBICOM Technical Report, Jan 2000

[18] H. J. Thomas et al., "An experimental study of the propagation of 55 GHz millimeter waves in an urban mobile radio environment," IEEE Trans. Veh. Tech., vol. 43, no. 1, pp. 140-146, Feb 1994.

[19] H. B Yang, M. H. A. J. Herben and P. F. M. Smulders, "Impact of Antenna Pattern and Reflective Environment on 60 GHz Indoor Radio Channel Characteristics, "IEEE Antennas and Wireless Propagation Letter, Vol. 4, 2005.

[20] S. Collonge, G. Zaharia and G. E. Zein, "Influence of the human activity on wideband characteristics of the 60GHz indoor radio channel," IEEE Trans. Wireless Comm. vol. 3, no. 6, pp. 2389-2406, Nov 2004.

[21] P. F. M. Smulders, "Broadband Wireless LANs: A Feasibility Study," Ph.D. Thesis, Eindhoven University, 1995

[22] A. Sadri, A. Maltsev and A. Davydov., "IMST Time Angular Characteristics Analysis," IEEE 802.15-06-0141-01-003c, Denver, USA, Mar 2006.

[23] A. Saleh and R. Valenzuela, "A Statistical Model for Indoor Multipath Propagation," IEEE J. Select. Areas Commun., Vol. SAC-5, No. 2, pp. 128-137, Feb. 1987.

[24] Q. Spencer, B. D., Jeffs, M. A. Jensen and A. L. Swindlehurst, "Modeling the Statistical Time and Angle of Arrival Characteristics," IEEE J. Sel. Areas Commun., Vol. 18, No. 3, pp. 347-360, Mar. 2000.

[25] C. -C. Chong, C, -M. Tan. D. I. Laurenson, S. McLaughlin, M. A. Beach, and A. R. Nix, "A new statistical wideband spatio-temporal channel model for 5-GHz band WLAN systems," IEEE J. Sel. Areas Commun., vol. 21, no. 2, pp. 139–150, Feb. 2003.

[26] R. C. Qiu and I. Lu, "Multipath resolving with frequency dependence for wideband wireless channel modeling," IEEE Trans. Vech. Technol., vol. 48, no. 1, pp. 273–285, Jan 1999.

[27] S. Emami, Z. Lai, A. Mathew and B. Gaucher, "Channel Model Based on IBM Measured Data," IEEE 802.15-06-0191-00-003c.

[28] M. S. Choi, G. Grosskopf and D. Rohde," Statistical Characteristics of 60 GHz Wideband Indoor Propagation Channel, IEEE PIMRC'05, Sept. 2005.

[29] M. Steinbauer and A. F. Molisch, "Directional channel models", Chapter 3.2 (pp. 132-193) of "Flexible Personalized Wireless Communications", 2001, John Wiley & Sons, U.K..

[30] C. -C. Chong and S. K. Yong, "A Generic Statistical-Based UWB Channel Model for High-Rise Apartments," IEEE Trans. Antennas Propat. , vol. 53, no. 8, pp 2389-2399, Aug. 2005.

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