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High Capacity RoF Links at 75-300 GHz

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Abstract: In this paper, we perform a feasibility study on the mm-wave radio technology at the range of 75-300 GHz. Our goal is to analyze the role of the antenna directivity to provide sufficient power margin for link designs beyond 100 Gbps.

1. Introduction

Wireless data communication in low frequency bands (less than 10GHz) are about to congest, and research is now focusing on how to use higher frequency bands [1,2]. The underexploited higher frequency range of 75-300 GHz is becoming a relevant research topic due to its capability to offer an even wider bandwidth for even faster gigabit-class wireless access links. However, the utilization of higher frequencies towards mm-wave range implies dealing with drastic signal attenuation due to severe free space losses. On the other hand, licenses restrictions in many countries set up limits to the maximum equivalent isotropically radiated power (EIRP) of the transmitter. Discussions on the power budget of wireless links for broadband mm-wave communications recommend that the EIRP must be restricted to 20 dBm. Therefore, in mm-wave range, an omnidirectional approach for receiver (Rx) and transmitter (Tx) antennas will not result in Gbps capacity links [3]. Directive antennas provide a solution to enable multi Gbps links over the entire mm-wave range [3]. Nevertheless, a precise antenna alignment cannot always be achieved, especially if the end-user is involved in the alignment process. Even in case of automatic electronic steering, accuracy may be limited, leading to capacity limitations due to non-precise transmitter-receiver alignment [4,5]. Therefore we believe that impact of antenna misalignment with respect to the intended beam direction must be considered in capacity analysis for mm-wave links. In this paper, we study the effect of antenna misalignment in mm-wave links whose signal generation is supported by photonic technologies [8]. We evaluate the antenna gain as a compromise against misalignment for a horn antenna operating at 300 GHz. We believe that the adoption of highly directive antennas can be seen as the enabling path towards the use of higher frequencies while complying with EIRP restrictions.

2. Feasibility Study

A) *Capacity Analysis of sub-THz Links*

Studies on radio-over-fiber with system bandwidth of 17.5 GHz and 25 GHz, operating at fixed carrier frequency of 92.5 GHz and 282.5 GHz, respectively, have been recently conducted [1,2]. These studies provide relevant link design guidelines towards achieving 100 Gbps data transmission using *M*-ary modulation formats. Following the same methodology it is possible to generalize such analysis for a range of carrier frequencies of 75-300 GHz, and for a range of bandwidths of 17.5-112.5 GHz. This analysis will permit us to observe crucial relations regarding required research and development towards overcoming the challenge associated with achieving 100 Gbps wireless links in mm-wave transmissions. Considering transmission links under LOS point-to-point (p2p) configuration with one Tx and one Rx, we calculate the theoretical Shannon-Hartley theorem for a channel with the signal-to-noise ratio (SNR) given in the far field region by

$$SNR = P_T + G_T + G_R - L_{FS} - IL - (N_0 + 10log_{10}B + NF) \qquad (1)$$

where P_T is the total transmitter power of a signal with bandwidth B, G_T and G_R are antenna gains on the Tx and Rx sides correspondingly, IL represents implementations losses, N_0 is the Johnson-Nyquist noise and NF represents the system's noise figure. Path loss L_{FS} has been conducted by the Log-distance path loss model for the free space propagation [7]. Inserting (1) into the well-known Shannon capacity formula, $C = B\log_2(SNR + 1)$, the maximum achievable capacity in additive white Gaussian noise (AWGN) channels can be computed.

Figures 1 and 2 present the computed channel theoretical Shannon's capacity for multiple combinations of i) operational frequency and ii) system bandwidth versus SNR conditions derived from (1), with NF = 6 dB, I_L = 6 dB and N_0 = 174dBm/Hz, for distances d of 1 m (orange) and 7 m (blue). The gray-toned surface demarks the 100 Gbps frontier at the z-plane. The color tones reveal how much SNR is imposed to the systems for combinations of i) operational frequency versus antenna gains for Figure 1 and ii) system bandwidth versus antenna gains for Figure 2. The SNR values vary from -35 dB (white) to 50 dB (black) for Figure 1 and from -40 dB to 40 dB for Figure 2. All simulations supposed power transmissions of 0 dB.

According to Figure 1, it can be seen that in a power-limited regime an increase in operating frequency implies in large reduction of capacity. This effect can be attributed to the fact that higher frequencies are associated with more losses due transmission in wireless medium. On the other hand, for the case when signal energy becomes less of a concern, increasing the system's operational frequency implies in less losses of capacity. For example, at a $d = 1$ m, an increasing in frequency from 92.5 GHz to 282.5 GHz, for an antenna's combined gain of 0 dB, one can see a reduction of capacity of 90 %, while the same increasing in frequency for a gain of 80 dB implies in a reduction of only 20 %. Figure 2 shows how, as bandwidth grows, enhancing the antenna gains results in larger capacities. It is noticeable how large capacities are obtained (~2 Tbps) given enough bandwidth and gains. That is a reasonable motivation to combine higher frequencies with sufficiently well-designed antennas for large bandwidth operation.

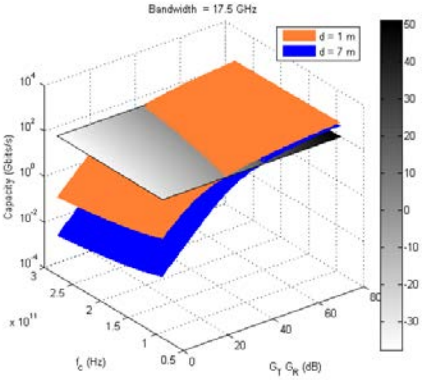

Fig. 1: Capacities for combinations of operational frequency and antenna combined gains for a fixed bandwidth of 17.5 GHz.

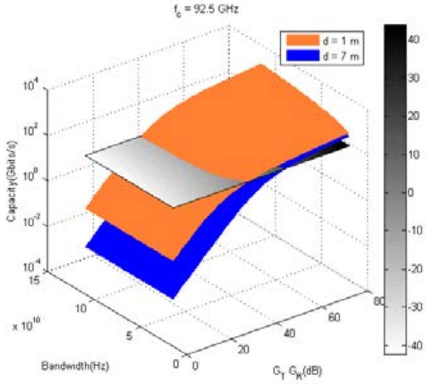

Fig. 2: Capacities for combinations of operational bandwidth and antenna combined gains for a fixed frequency of 92.5 GHz.

B) Antenna Design Guidelines for sub-THz Communications

The horn antenna design provides a straight solution that can operate over a wide frequency range and support wide bandwidth data transmission. In order to estimate the impact of antenna misalignment on mm-wave communication under realistic conditions, we use a standard pyramidal horn design (see Figures 3 and 4) which generates a narrow signal beam, and meantime is easy to fabricate with nowadays' technology [2]. An antenna with such directivity and power characteristics can be obtained from the geometrical parameters provided in Table I.

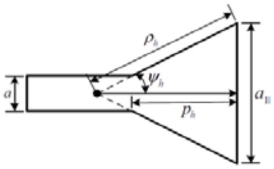

Fig. 3: H-plane view of used horn antenna.

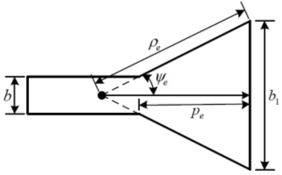

Fig. 4: E-plane view of used horn antenna.

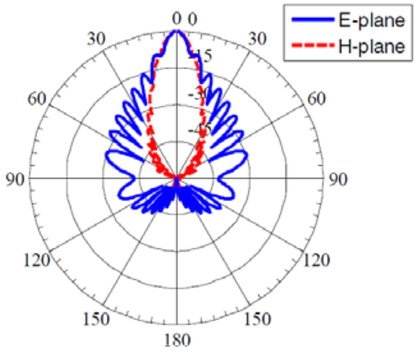

Fig. 5: Radiation patterns in both E and H planes for used antenna.

TABLE I – GEOMETRICAL PARAMETERS OF LOW-THZ PYRAMIDAL HORN ANTENNA.

Parameters	Value
a_1	0.97 cm
b_1	0.79 cm
a	0.0863 cm
b	0.0431 cm
ρ_e	3.12 cm
ρ_h	3.24 cm
ψ_e	7.27°
ψ_h	8.74°
p_e	2.93 cm
p_h	2.93 cm

With the aim to assess the impact of misalignments on the effective antenna gain, the alignment error is evaluated in terms of misalignment angle with respect to the main beam direction. In this work we consider that a Gaussian beam model with the gain

$$G(\emptyset,\theta) = G_0 . e^{-\left(\frac{\emptyset,\emptyset_0}{\sigma_{g,\emptyset}}\right)^2} . e^{-\left(\frac{\theta,\theta_0}{\sigma_{g,\theta}}\right)^2} \quad (2)$$

will be used to model realistic antenna radiation patterns [6]. The values ϕ and θ are the azimuth and elevation, respectively, with ϕ_0 and θ_0 denoting the pointing direction of the antenna in which the maximum gain G_0 is achieved, determined according to the two antenna method [7]. The values $\sigma_{g,\phi}$ and $\sigma_{g,\theta}$ provide a measure for the width of the beam and relate to the HPBW (half power beam-width) via $HPBW = \sigma_{g,\phi,\theta} . \sqrt{4. \ln 2}$ in the respective dimension. Without loss of generality, we consider that the Rx is fixed and the Tx is mobile.

Figure 6 present the computed channel capacity for different angles of misalignment for both H-plane (with a HPBW of 6.4^{o}, at $\Delta\phi$ ^{o} axis) and E-plane (with a HPBW of 5.2^{o}, at $\Delta\theta^{o}$ axis) at fixed operational frequency and system bandwidth of 17.5 GHz and 282.5, respectively. It is possible to conclude from Figure 6's lower borders that the tighter the antenna's HPBW is, the more susceptible to the impact of misalignment it becomes. This is an expected result considering that the radiated power of directive antennas should become more concentrated as HPBW decreases. As Figures 1 and 2, the gray-toned surface of Figure 6 demarks the 100 Gbps frontier at the z-plane. The surface's color scale translates the directivity gains obtained by the directivity, with maximum gain of 27.6 dB at $\phi = \theta = 0$, in which a capacity of ~190 Gbps is achieved. Figure 6 also shows that capacities of 100 Gbps can be achieved even with some steering misalignment between Tx and Rx antennas.

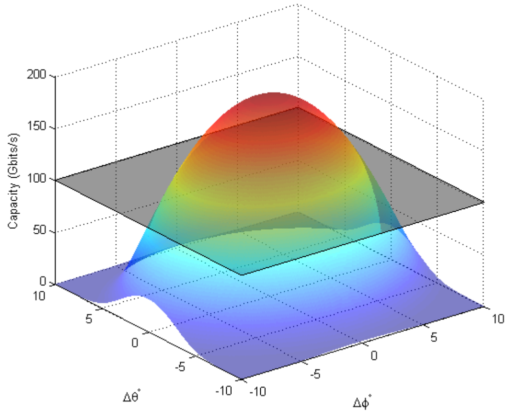

Fig. 6: Channel capacity over different angles of misalignment for E-plane and H-plane.

3. Conclusions

In this study, we investigate the channel theoretical Shannon's capacity for multiple combinations of operational frequency, system bandwidth and combined antenna gains versus SNR conditions considering transmission links under LOS point-to-point (p2p) configuration with one mobile Tx and one fixed Rx. Moreover, we estimate the impact of antenna misalignment on mm-wave communication under realistic conditions by using a real pyramidal horn design. We provide discussions about motives to combine increasingly higher frequencies with sufficiently well-designed antennas stressing that the tighter the antenna's HPBW is, more susceptible to the impact of misalignment it becomes. These findings extend those of [1,2] in the analysis of hybrid optical fiber-wireless links towards achieving capacities of 100 Gbps. In addition, we provide a multidimensional-view framework for measuring crucial parameters on the design of x100 Gbps links at mm-wave frequencies. This study confirms that the use of directive antennas can be seen as the enabling path towards the use of higher frequencies while complying with EIRP restrictions. Together with the fact that mm-wave frequencies can reduce inter cell interference by the high losses caused by walls [3], our results provide key guidelines for enabling Radio-over-Fiber (RoF) systems, whereupon: a) improved network coverage is given to a relatively small area; and b) complete coverage is combined with high data throughput. Future work should consider experimental measurements through several practical scenarios [8].

4. Acknowledgement

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