Overview of antenna problems and solutions for multi-Gb/s links

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Abstract—Fundamental limitations in link budgets for wireless indoor networks are considered for millimeter and THz frequencies. Single small antennas at those frequencies are a bottleneck due to the small absorption areas and the ensuing path loss. Although different for LOS links and links in diffuse surroundings, there are no theoretical limitations, if complexity is ignored. Complexity and power consumption may be reduced by using analog solutions where possible, and in the paper we focus on phase conjugation methods, specifically in retrodirective arrays. Considering power solutions only, mimicking optical networks, we call attention to an array of rectennas.

Index Terms—antennas, millimeter, THz, rectenna, retrodirective

I. INTRODUCTION

There is a continued interest in higher and higher data rates for applications in indoor environments, and if Edholm’s law [1] continues to be valid we can expect wireless networks to approach the data rates of tethered networks. For multi-Gb/s solutions the only option is to use higher frequencies. It is, however, not known today what practical solutions are possible considering the high path losses, where the antenna is a key bottleneck. The solution depends on whether it is a case of line-of-sight (LOS) or non-line-of-sight with random scattering from objects and walls in the room, and also whether it is a fixed installation or a nomadic one, where the devices are stationary during use, but may be moved around. The situation is similar to the infrared case, discussed in detail by Barry [2].

Laskar et al [3] find that the time is ready for millimetre integrated circuits (around 60 GHz) for the consumer market due to the emergence of CMOS-based circuits. Piesiewicz et al [4, 5] go several steps further studying indoor coverage at 350 GHz, and find that high gain LOS antennas are needed, although the environment may be enhanced by placing dielectric mirrors for further scattering as passive repeaters in a NLOS scenario. It is often mentioned that atmospheric attenuation is a problem, but there are many frequency windows, such as a 47 GHz window at 350 GHz with an attenuation of 3 dB/km [5], hardly a problem indoors. The problem lies more in the shadowing from obstacles and lack of penetration through walls. This calls for solutions taking advantage of the diffuse scattering in the room, as described in [6] for 6 GHz.

The actual data rates achieved up to now varies with distance, 5 Gb/s at 5 meters (quoted in [3]) for 60 GHz carrier, and 3 Gb/s for a few meters [7] for LOS and simple horn antennas at a frequency of 120 GHz.

II. THEORETICAL LIMITATIONS

The path loss is given by Friis’ law

\[ \frac{P_r}{P_t} = G_t G_r \left( \frac{\lambda}{4\pi R} \right)^2 \]  
\[ \frac{P_r}{P_t} = \frac{A_t A_r}{(\lambda R)^2} \]

where \( P_r \) is the received power, \( P_t \) the transmitted power, \( G_t \) and \( G_r \) the gains of the transmitter and receiver antennas, \( \lambda \) the wavelength, and \( R \) the distance. These are given in two versions, depending on whether the antennas are defined by gain or directivity \( G \) or by effective aperture \( A \), respectively. The two are related by the fundamental relationship

\[ A = G \frac{\lambda^2}{4\pi} \]

for a lossless antenna in free space. For fixed small gain (1a) the small wavelength is a problem, while it is the opposite for fixed aperture (1b), where the higher the frequency the better. This situation occurs for fixed directive installations, where for example, an aperture of 2 cm * 2 cm gives a gain of 27 dB at 100 GHz, and a path loss of 37 dB at 10 m. It is assumed that there are identical antennas at the two ends. A high directivity has its own problems with sensitivity to small pointing errors.

The theoretical solution for NLOS or nomadic LOS is of course to split the aperture up into many small elements with adaptive combining and signal processing. In the example above we need around 180 antenna elements spaced half-a-wavelength, which is an appalling figure seen from a signal processing and circuits point of view. Dividing the area \( A \) in sections \( \Delta A = \alpha \lambda^2 \) the number of antennas equals

\[ N = \frac{A}{\alpha \lambda^2} \]

where \( \alpha \) is a constant, here chosen as 0.25.

In an LOS situation the gain of an array (with uncoupled elements) grows linearly with \( N \), while in the case of a random environment and complex conjugate match at each end the gain only grows as \( 2\sqrt{N} \) (Andersen [8]). This has the consequence that the path loss in the random case becomes frequency independent, under the assumption that the number of elements keeps growing with frequency for a constant aperture (3). The path loss is shown in Figure 1 for the above mentioned case of a 2 by 2 cm aperture, and a distance of 10 m for frequencies up to 100 GHz. For the random case it is the
A case of an asymptotic upper bound, less accurate at the low frequency end.

Fig. 1 Path loss between two identical arrays for LOS and random NLOS. The upper curve is for single isotropic antenna.

It should be recalled that for the random case the gain found is only the largest of many parallel channels. This MIMO case is however not treated here.

It is apparent from Fig. 1 that there are large gains to be obtained in introducing adaptive arrays, about 55 dB for the LOS case and 30 dB for the random case. In practice it will be a mixture of the two. The price is increased complexity and cost, and in the following we shall look at some less complex solutions than the ideal one.

### III. RETRODIRECTIVE ARRAYS

The purpose of the array antennas at the two ends is to achieve maximum gain between the two antennas. This is similar to the well-known retrodirective arrays for scatterers, where the scattered power is maximum back towards the transmitter. The key to this is that the phase at each antenna element is the negative of the received phase, also known as phase conjugation. For a receiver it would correspond to maximum ratio combining in a diversity system, so the technique will work not only in LOS cases, but in general for obtaining maximum received power. As indicated in [8] a simple iterative technique will maximise the power at both ends.

It is interesting to observe that focusing arrays in time and space uses a similar technique for imaging [9] and communications [10] under the name time reversal technique. Technically there are various ways to obtain the phase conjugation, the simplest being based on van Atta arrays [11,12], where the geometry of linear arrays is arranged such that the scattered fields are returned in the opposite direction of the incident field, Figure 2.

The three elements to the left are placed in the opposite order of those to the right, such that the phase conjugation is achieved by geometry alone. The connecting lines have the same electrical length. In the original van Atta array there are no amplifiers, but they will enhance the retrodirective beam and allow for modulation [13]. As shown in the figure there will also be a component in the symmetric reflection direction. Different ways of obtaining phase conjugation using mixers and filters are discussed in [14, 15], where the simplest method applies a local oscillator signal at twice the RF frequency and the output signal contains the negative of the phase of the input signal, but also solutions with lower LO frequencies are suggested.

It is important to realise that the principles will work both for single LOS rays as well as multipath signals from different directions. This is illustrated in Figure 3, which shows the iterative technique for a 5 element array in a Rayleigh environment with a resulting gain of 11 dB relative to one element.

Figure 3 The mean gain for two 5-element arrays in a Rayleigh uncorrelated environment by the iterative technique.
IV. RECTENNAS

At optical and infrared communications it is power communications which is possible, since phase is difficult to handle and highly variable [2]. At millimeter and THz frequencies the same could very well be true and also acceptable since the bandwidths are so high that simple power modulation schemes will be sufficient, compared with more efficient phase modulations.

The simplest power receiving antenna is the so called rectenna, a combination of a rectifier and an antenna. The modulated signals are then combined after the rectifier. Work on rectennas goes back to the ideas of power transmission from solar panels in space [16], but recently there has been renewed interest in connection with powering sensors through the air. Conversion efficiencies from RF to DC (or baseband) of the order 50% is possible [17, 18]. The sketch in Figure 4 shows the idea.

![Figure 4 An array of rectennas combined at baseband.](image_url)

The use of an array of rectennas is similar to infrared communications with direct conversion [2] on a square-law detector area. Since the area is many wavelengths the summation of powers leads to an efficient diversity reception, mitigating any fading patterns from multipath reception. The drawback lies in the solution being receive only, so the transmitter will be illuminating a large angular sector.

V. CONCLUSIONS

Communication at millimeter and sub-millimeter wavelengths in indoor environments suffers from large pathloss due to electrically small antennas. The only exception is for fixed LOS, where relatively small aperture antennas like a parabolic dish can be pointed permanently. In random environments or when antennas are moved around, it is necessary with some adaptive solutions. Realization of integrated antennas at millimeter frequencies is discussed in a recent book [19].

The emphasis in the paper is on quasi-analog solutions with various ways of obtaining the phase conjugation necessary for maximum power transfer. One way is to use mixing where by proper filtering a sideband with conjugate signals is obtained. Self-focusing arrays such as retrodirective arrays were originally proposed for enhanced scattering back to the transmitter, but they have the potential to be used in duplex communications as well. A solution where both sides are optimized may be achieved by iteration. The last technique suggested borrows from power transmission and from infrared and optical technology, where only power is received. This is a drawback from a modulation point of view, but the promised bandwidths are so high, that it seems to be a price worth paying. The power is obtained by immediate detection at the antenna and subsequent filtering to preserve and combine the baseband signals. Like in the other solutions the fading is mitigated, the disadvantage being that it is only a receive solution.

REFERENCES


