Antenna evaluation for communications with diversity/MIMO

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Introduction

This short-course addresses the evaluation of antennas for communications. Most antenna applications concern a digital communications link. The antenna gain has a direct impact on the link performance including the spectral efficiency. The classical directive gain and its measurement are reviewed with the natural progression to the distributed gain and the diversity gain for antennas designed for multipath situations. With most links operating in multipath, multi-element antennas with high distributed gain and good diversity performance are required. Developing compact multi-element antennas with statistical performance measures requires convenient experimental evaluation techniques.

Summary

Antenna performance evaluation is not only part of the communications system analysis and design, but it is also part of the iterative process of compact antenna design. Consequently, convenient evaluation techniques are important. Both theoretical and practical aspects are addressed for evaluating antennas for high capacity efficiency . This calls for an emphasis on the various efficiency and gain factors which feature in the multipath communications link analysis. Here, the antenna polarization efficiency becomes incorporated into the distributed gain of the antenna element and is a major difference between classical line-of sight links and diversity links for multipath.

The compactness of an antenna system is important for both the cost of the terminal and its market acceptability. The trade-off between impedance bandwidth and antenna compactness offers a helpful comparison for different types of antenna elements. For evaluating multi-element antennas for multipath environments, the diversity gain offers a robust performance measure. However, the diversity gain is a statistical quantity and to produce a direct estimate of it requires a considerable measurement campaign with considerable signal processing. Moreover, the diversity gain does not provide the specific information for how to improve the configuration of the antenna elements. The required information is the set of mean branch powers and in particular the set of correlation coefficients between the loaded antenna signals. Direct estimates of these statistics would be made from sampling the antenna signals when the antenna is operating in different multipath scenarios. However, gathering and using such samples brings difficulties in the interpretation and repeatability, and the sample size required for accurate estimates is large which means a large measurement effort. These factors highlight a need for a more convenient evaluation technique, especially for the antenna design process, which is normally iterative. Measuring the antenna impedances, together with modest off-line signal processing, offers such an alternative, although this approach requires certain conditions regarding both the propagation environment and the antenna elements. If these conditions hold, then the diversity gain can be estimated from the impedance measurement. For designing multi-element antenna configurations, the diversity gain can be couched as an equivalent number of ideal branches, i.e., an effective diversity order. The effective diversity order is a performance metric which is suitable for the designer to trade-off against compactness of the multi-element antenna configuration. This is illustrated through the use of design examples in which the antenna is made sufficiently compact to force the effective order of diversity to be significantly reduced from the physical number of branches.

Background and motivation: digital communications link performance

Most antenna applications are for the transport of digital information. The link performance is measured by a statistic - the throughput of correctly detected bits per bandwidth, or *capacity efficiency*. For transmission, the digital data is typically encoded into a finite alphabet of analogue symbols comprising several bits of information. If the bit-error-ratio (BER) can be kept to less than about 10^{-4}, then forward error correction coding can reduce the coded bit error rate to a negligible value. For most applications, a negligible error rate is not necessary, and an acceptable uncoded BER for wireless communications can be as low as 10^{-3} or even 10^{-2}. A direct evaluation of the capacity of a link, or its digital outage, etc., is relatively straightforward, involving digital test sequence analysis. But such an evaluation, dealing with only the data channel, does not reveal the mechanisms causing the bit errors, or where link improvements could be made within the system. While fractions of a dB improvement are a cause for celebration in data coding research, much larger improvements, especially in most personal and mobile links, can be made at the antennas, through better matching (spatial, polarization and impedance), leading to higher gain designs. Figure 1 depicts the channels of a communications link.

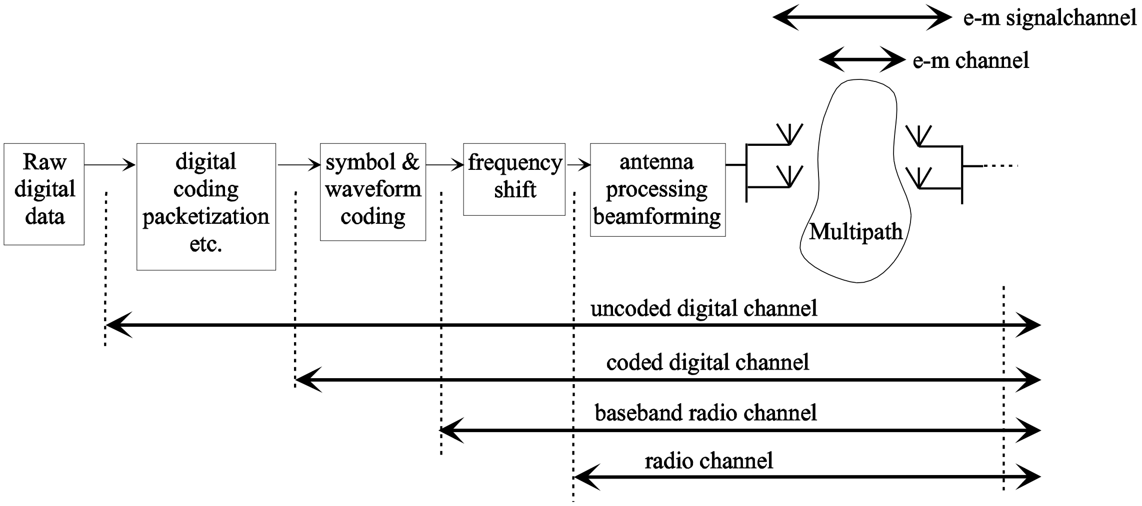

Figure 1. *The channels of a digital link. Evaluation of the link is simplest using digital data sequences, but this reveals little about the RF performance and how it may be changed to improve the link. With the communications signal processing capability having reached its limits of capacity improvement for a channel, it is the performance of the antenna, and in particular the multi-element antenna, that remain the source of potential capacity improvement.*

Independent of the encoding and alphabet size, the primary parameter which defines the average uncoded BER is the average energy-per-bit over the noise energy density, denoted ϵ_b/N_0, where the energy averaging is over the alphabet of symbols. The ϵ_b/N_0 relates directly to the signal-to-noise ratio (SNR) at the receiver, see (1) below. The instantaneous SNR is calculated by time averaging over several RF cycles. The noise is normally dominated by the receiver thermal noise which is otherwise independent of the wireless link. In a changing link, such as in mobile communications, the SNR becomes an a random variable, and its distribution is estimated over either a fixed duration, or over a set of environments, for link characterization.

The Shannon capacity efficiency, in C bits per second, over the bandwidth used, B Hz, is related to the ϵ_b/N_0 by Shannon's law

$$\frac{C}{B} = \log_2\left(1 + \frac{C}{B}\frac{\epsilon_B}{N_0}\right) = \log_2(1 + SNR). \qquad (1)$$

This leads to the limiting wireless link capacity (and also the achievable, or *practicable capacity*), and the capacity efficiency, being directly related to the signal energy at the receiver. The signal energy, for a given signal design and regulated transmitter amplification level, is determined by the path loss and antenna gains. The importance of the capacity efficiency metric lies with the increasing need to use wisely the radio spectrum, a finite and shared resource.

With communications signal processing techniques such as equalization, rake reception, and error correction coding, wireless digital communications systems can now operate within fractions of a dB (in the SNR) of the Shannon capacity limit. In this sense, the signal processing capability has progressed to achieve effective saturation of the Shannon capacity efficiency.

In the meantime, the antenna gain has not only maintained its fundamental role in the wireless link, but has now become the only capacity-limiting factor left within the control of the link designer. If the antenna's physical aperture can be allowed to increase in order to increase the antenna gain, then the capacity efficiency can increase. Such a capacity efficiency increase is unbounded, at least in a mathematical sense. The increased aperture can be achieved using multi-element antennas, and the associated signal processing technology, together called multiple-input, multiple output (MIMO), has opened up relatively new possibilities for the capacity efficiency. Consequently, multi-element antennas are key for high capacity efficiency systems.

To illustrate the power of multi-element antennas, the Shannon capacity efficiency for M_{tx} combined transmit antennas and $M_{rx} \geq M_{tx}$ receive antennas, can be written in an approximate form

$$\begin{aligned} \frac{C}{B} &\approx M_{tx}\log_2\left(1 + \frac{M_{rx}}{M_{tx}} SNR\right); \\ &\approx M \;\log_2(1 + SNR), \qquad M_{rx} = M_{tx} = M. \end{aligned} \qquad (2)$$

This is a parallel-channels capacity formula [c.f., Gallagher, 1968]. It relates to (1) in that there are M_{tx} independent (i.e., parallel) channels with the total transmit power divided evenly between the channels. The channels each have the same mean SNR, which is now SNR/M_{tx}, and also there is a receiving array gain of M_{rx} for each channel. The simplification in (2) follows from having the same number of elements at each end of the link. Equation (2) can be considered as an upper limit to the Shannon capacity for MIMO links, both for the known channel (at the transmitter) case and the unknown channel case.

In a MIMO link, the antenna signals should be mutually uncorrelated over the fading from the multipath propagation. Relative to capacity efficiency limits for MIMO operating in multipath, the parallel channels equation above is optimistic by a few bits/sec/Hz for modest antenna numbers, say M<12. However, the approximation is highly illuminating: there is a striking comparison between the single channel case of (1) and the MIMO case of (2). While the receiver SNR still has the same logarithmic impact on the capacity efficiency as in the classical Shannon relationship, the linear dependence on M illustrates the unbounded (except by practicable considerations) growth of capacity efficiency with antenna dimension. For a fixed spectral cost, i.e., bandwidth and transmit power, the capacity can grow by simply adding antennas. The associated signal processing required for this is currently under development for commercially viable systems.

If there is unobstructed line-of-sight (LOS) between the M-element transmit and receive arrays, then the capacity efficiency will exceed that of the multipath case. In this case, conventional, directional beamforming would be used.

Interference-limited links

Most applications occupy spectrum which is shared, intentionally or inadvertently, and the signals from other users, or interference, dominates the thermal noise as the unwanted signal. The primary parameter for communications capacity, instead of being the SNR, now becomes the signal-to-interference plus noise ratio, SINR.

With multi-element antennas, we can also apply array signal processing techniques to suppress the interference power, which of course increases the SINR. This is a compounding motivation for using multi-element antennas in communications.

In this short-course, we develop techniques for the evaluation of antennas that can provide the signals suitable for realization of high capacity efficiencies.

Basic reference material

Vaughan, R.G., Andersen, J.B., *Channels, Propagation and Antennas in Mobile Communications*, IEE, London, UK, 2003.

Vaughan, R.G., *Antenna Evaluation for Communications With Diversity/MIMO*, Chapter 12 of *Printed Antennas for Wireless Systems and Related Topics*, to be published 2006, Editor: Rod Waterhouse.

Plus many others!
