Antenna Design and Site Planning Considerations for MIMO

(Invited Paper)

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***Abstract*— The capacity and reliability of multiple-input multiple-output (MIMO) wireless communications systems may be sensitive to the design of the antenna arrays employed at the transmitter and receiver, as well as to the nature of the propagation between the arrays. This paper discusses the emerging methodology of array design for indoor MIMO systems used to implement wireless local area networks, and discusses some aspects of site planning which are likely to influence design choices. Some guidelines are described for choosing the number, type, and polarization of elements; element spacing and geometry; and location and orientation of arrays within rooms and hallways.**

I. Introduction

Propagation in indoor wireless systems operating in the UHF band and above is characterized by fading due to copious multipath components which are typically unresolved in the time domain but with uncorrelated and uniformly distributed phases. In the absence of interference, the resulting "flat" Rayleigh or Ricean fading is typically the limiting factor in the link capacity when the time-average signal-to-noise ratio (SNR) is moderate to high. As a countermeasure, arrays of antennas can be employed to obtain a degree of diversity. If the average SNR is relatively low, arrays can alternatively be used for beamforming, which can be defined as an attempt to manipulate the array pattern to increase SNR.

In a multiple-input multiple-output (MIMO) system, both ends of the link are equipped with arrays, and the MIMO channel can be interpreted as a superposition of $k \leq min\{N_T, N_R\}$ uncorrelated spatial subchannels, where k is referred to as the rank of the MIMO channel and N_T and N_R are the number of elements in the transmit and receive arrays, respectively. k is determined jointly by the propagation channel and the array, and can be a small as 1. If the subchannels are selected optimally, the capacity of a MIMO channel is the sum of the capacities of the subchannels. The subchannel capacities are determined by the Shannon bound, which is proportional to $\log_2\{1+\text{SNR}_i\}$, where SNR_i denotes the instantaneous SNR of the i^{th} subchannel. Thus, achieving a k-fold capacity increase via MIMO requires: (1) a propagation channel capable of supporting at least k independent subchannels, and (2) arrays of at least k elements each which can "access" these subchannels with useable SNR. In practice, either (1) or (2) can limit the capacity of a MIMO channel. In this paper, we refer to the number of subchannels available with "useable" SNR as the *effective* rank k_e of the MIMO channel, with $k_e \leq k$. This a useful concept since many MIMO channels in actual practice have full rank (i.e., $k = min\{N_T, N_R\}$) but with only k_e subchannels having SNR sufficiently large to contribute significantly to the MIMO channel capacity.

Array design for indoor wireless communications has traditionally not been a topic of great concern to either academia or industry. However, the emergence of MIMO has reinvigorated interest in this topic somewhat, since the array plays a more vital role by determining k_e and hence may be a limiting factor in determining capacity. At the same time, cost and complexity issues often limit interest to systems with just 2–3 elements on existing form factors, which does not offer much opportunity for optimization. Nevertheless, there may be opportunities to optimize these "small-N" designs, as well as opportunities to implement larger arrays as might be considered as part of new deployments of infrastructure. Developing guidelines for placement (location and orientation) of such arrays is also a potentially interesting problem for MIMO systems.

Jensen and Wallace provided an excellent tutorial and review of MIMO from an antennas & propagation perspective in [1]. This paper addresses specifically the emerging methodology of array design for indoor MIMO systems, which includes non-MIMO systems ($N_T = 1$ or $N_R = 1$; thus, $k = 1$) as special cases. Design goals considered include: (1) maximizing subchannel SNR over the coverage area, which constrains element design; (2) maximizing the effective diversity order r, which is determined by the number, geometry, and spacings between elements; (3) minimizing the number of elements as well as the overall size of the array so as to reduce both size and cost, and (4) (for MIMO specifically) to maximize k_e. Since both the r and k are determined by the combined (propagation + array) channel, the topic of array design is difficult to separate from that of site planning. Thus, this paper also addresses site-specific considerations in the design of arrays.

The remainder of this paper is organized as follows. Section II provides a brief review of the characteristics of indoor propagation at UHF frequencies. Section III describes some general principles of array design. Sections IV and V describe

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design principles for rank-1 (diversity and beamforming) and MIMO arrays, respectively. This paper concludes with a discussion of site planning in Section VI, emphasizing some of the unique issues associated with hallways.

II. Characteristics of Indoor Propagation

The first consideration in the design of an antenna system for indoor wireless communications is the nature of the indoor propagation channel. The multipath contributing to flat fading may be spread over angles ranging from very large (e.g., within rooms) to very narrow (e.g., within long hallways). While the angle spread is often very large, it also tends to be "lumpy," being concentrated in elevation near the azimuthal plane, and within the azimuthal plane mostly in the form of discrete clusters (e.g., 4–10 such clusters at 5.2 GHz [2]) often associated with line-of-sight and specular reflection mechanisms. Diffraction contributes to blur the distinction between these clusters and to illuminate areas not accessible by line-of-sight and reflection mechanisms.

In typical office buildings, floors and ceilings are often conductive and efficiently reflect signal power, whereas walls tend to exhibit lossy dielectric characteristics, resulting in a variety of behaviors ranging from near-transparence to near-total reflection [3]. It has been reported that vertical polarization normally propagates slightly better than horizontal [4]. Within rooms, clutter and other factors results in cross-polarization (i.e., received power in a polarization orthogonal to that in which it was transmit) which is typically very large; whereas within hallways, cross-polarization tends to be relatively low, on the order of -15 dB [4].

III. General Array Design

Element Design: As with any array, it is desirable to use elements with patterns that are well-matched to the range of directions over which incident power can be expected. Since the angle spread is usually quite large in azimuth and narrow in elevation, vertically-polarized dipoles or monopoles are a reasonable choice, and are implicitly assumed throughout most of this paper. However, other reasonable choices include patches, slots, and various other elements (helices, yagis) germane to special cases. It is sometimes tempting to incorporate some degree of pattern diversity – that is, to intentionally vary the patterns with the goal of decreasing the correlation between elements. While this is potentially helpful from a diversity perspective, there are pitfalls; these are discussed in Section V. Using multiple polarizations (e.g., some elements horizontal) is a reasonable choice in cluttered rooms and other environments where the cross-polarization is large and the size of the array must be minimized.

Number of Elements: In general, the number of elements N (used here to refer generically to either N_T or N_R) must be $\geq r$ to achieve diversity order r for any given rank-1 subchannel and $\geq k$ to acheive k independent subchannels.

Array Volume: Usually, an explicit or implied requirement exists for the entire array including all elements to fit within a specified volume. Since an array consists of discrete elements, the volume is more properly described as a "geometry"; but for the purposes of this discussion the two concepts can be used interchangeably. Obviously, setting a given volume will constrain (upper bound) both r and k_e. A very small array can be constructed from 3 resonant dipoles arranged at right angles so as to access three orthogonal polarizations of the electric field at a point; if the angle spread is approximately isotropic then such an array yields $r = k_e = 3$ [5] and the volume is approximately $0.125\lambda^3$.[1] An even smaller version of this array is possible simply by reducing the length of the dipoles and matching to the resulting impedances; however one quickly encounters intractable difficulties with radiation efficiency and bandwidth narrowing as the element size is decreased [7]. For simplicity, the remainder of this paper assumes elements operating near resonance.

IV. Design for Rank-1

As pointed out in Section I, the MIMO channel can be interpreted as a superposition of rank-1 subchannels, where the role of either array (receive or transmit) on a subchannel basis is to facilitate diversity or beamforming. Thus, it is reasonable to consider first what is needed to make the array effective in either of these roles.

Optimizing Diversity when Angle Spread is Large: From a rank-1 diversity perspective, the performance that can be achieved by any array which must fit inside a specified volume depends primarily on the achievable element correlation. This in turn depends on the spatial autocorrelation function of the propagation channel. Since angle spread is usually large in the azimuthal plane, the resulting spatial autocorrelation function is given by $R(d) = J_0(2\pi d/\lambda)$, which is oscillatory with peak values that decay with increasing separation d [8]. As a result, d should nominally be on the order of wavelengths for elements to be consistently decorrelated. In this case, uniform linear arrays (ULAs) are attractive because they offer the maximum separation between adjacent elements consistent with the requirement that the separation between the outer elements be maximized.

Optimizing Diversity when Angle Spread is Not Large: The effect of narrowed angle spread is to broaden $R(d)$, thereby increasing the separation required to consistently achieve a given correlation, and thus increasing the volume required to obtain a given diversity order [9]. If it is reasonable to assume that the angle spread in the azimuthal plane is approximately isotropic (e.g., inside cluttered rooms), the orientation of the array within the azimuthal plane doesn't matter. However since the angle spread in the elevation plane is normally smaller, the array should normally lie *completely* in the azimuthal plane. It the azimuthal angle spread also favors some direction (e.g., in hallways), a ULA arranged perpendicular to the mean angle-of-arrival (AOA) is generally preferred if this AOA is known

[1] It is conceivable that the number of elements at a point could be increased to 6 by including the magnetic field components, resulting in $r = k_e = 6$; however it seems that even if such an array could be built, the fact that the angle spread is not exactly isotropic will limit the effective rank (at least) to 3 in this case as well [6].

and fixed [9]. The required separation between elements can be determined from the physically-intuitive rule of thumb is that the outer two elements of an array begin to decorrelate when array is large enough to resolve the angle spread. For example, a 15° angle spread will begin to decorrelate elements separated by $> 4\lambda$, since an array this large has a beamwidth (when pointed to broadside) which is $< 15^\circ$. If the angle spread is narrow and the mean AOA is not known, or if the angle spread is wide but sparse, then a geometry with rotational symmetry in the azimuthal plane is a better choice. The "Y" geometry has been suggested [10] and has the advantage over other geometries of having relatively low cost ($\propto N$) per unit aperture [11].

Overcoming Volume Limitations by Decreasing Spacings: Of course, it is often the case that a volume is too small to support the desired diversity order r_{goal} when $N = r_{goal}$. In this case, it is tempting to consider whether $N > r_{goal}$ within the same volume can achieve $r = r_{goal}$. Both the channel (spatial autocorrelation) and the array (mutual coupling) are limiting factors. The relevant question is this: To what degree can a closely spaced array of elements deliver the same diversity order as an array consisting of a smaller number of less tightly-coupled elements occupying a larger volume? A useful and physically-intuitive rule of thumb is that coupling becomes significant for spacings less than about $\sqrt{A_e}$, where A_e is the effective aperture of the element by itself in free space. For a vertically-polarized dipole, $A_e \approx 0.13\lambda^2$, so $\sqrt{A_e} \approx 0.36\lambda$ in the azimuthal plane. The deleterious effects of coupling become important at about the same distance [7]. Unless the coupling is explicitly accounted for in the design, this usually has the effect of altering the active impedance of the elements in an undesirable way, which in turn reduces radiation efficiency and ultimately results in a degradation of SNR. Thus even if diversity order is improved, capacity may not be. In this case, using orthogonal polarizations may offer a better solution even if the channel cross-polarization is low. Generally, once the mutual coupling becomes important, it is difficult to apply simple rules of thumb and a more rigorous analysis is required. This issue is addressed further in Section V.

Beamforming vs. Diversity: As noted in Section I, it is sometimes low SNR, as opposed to fading, that becomes the capacity-limiting impairment. For example, this might be the case along the fringe of a coverage area. If it is known in advance that this will typically be the case, then beamforming ability (specifically, the ability to increase average SNR through array gain) is probably more important than diversity order. In this case, inter-element correlation is not a constraint and thus there is less advantage in element spacings greater than $\sim \lambda/2$.

V. Design for MIMO

In general, MIMO channels that have full rank will exhibit uncorrelated elements. However, the converse is not true: low correlation by itself does not imply k (much less k_e) ≥ 1: The extreme example of this is the so-called "keyhole channel" for which elements can be fully decorrelated even though the propagation channel supports only $k = 1$ [12]. Therefore, some additional considerations are required to optimize the MIMO channel rank that an array can support, even if the array already effectively supports the desired subchannel diversity order and/or beamforming ability.

Volume and geometry requirements for which N elements yield a given k_e arise from considerations that are related to, but different from those that apply to r. Consider a simple MIMO channel consisting of two incident plane waves of equal power arriving from different directions and bearing uncorrelated signals. $k_e = 2$ is achieved if they can be spatially separated using beamformers, perhaps with the assistance of nulling. This requires only that the arrays have two elements with sufficient spacing to allow the maximum of each array pattern to be directed toward one plane wave while a null is directed toward the other. In other words, this array must be sufficiently large to resolve the individual AOAs.

The usual scenario, however, is that the angle spread is large and complex, so no obvious *geometrical* decomposition of the channel into uncorrelated subchannels is possible. In this case, the concept of rank becomes an ambiguous measure of performance because any decomposition of the MIMO channel is likely to result in subchannels with unequal SNRs. In this case, it is better to analyze the problem in terms of the *capacity* of MIMO channel, which is given by the famous generalization of the Shannon Bound by Foschini and Gans [13]. In that formulation, however, the effect of the array is embedded in the channel description, and so yields relatively little insight into the problem of how to properly design an array for good MIMO capacity. Wallace and Jensen [14] provide an alternative theoretical framework which is useful for understanding the "intrinsic capacity" of a volume, which depends only on the propagation channel and the dimensions of the volume, and thus provides a useful upper bound for characterizing the performance of an array which occupies that volume. Such an analysis can also be useful in establishing the maximum number of elements which can be effectively employed within a volume. Since the cost of a MIMO system is roughly proportional to N, understanding this "knee in the curve" is perhaps the single most useful piece of information from an economic perspective! For dipole-like antennas in a propagation environment with very wide angle spread, it is found that additional elements contribute negligibly to the capacity as the spacing decreases beyond $\sim \lambda/3$, which is consistent with the 0.36λ rule of thumb (described above) and the findings of other studies, such as [15].

MIMO with Narrow Angle Spread: An important special case is that of relatively narrow angle spread, such as might be encountered along hallways or subway tunnels. In these cases, it is known that a ULA oriented with its broadside facing the direction of the mean AOA yields good performance [16], [17]. This is probably attributable to a combination of two factors: (1) as above, if the array is capable of resolving the angle spread, it is more likely to achieve the spatial decomposition of the propagation channel into the multiple uncorrelated subchannels required for MIMO; and (2) assuming the element spacing is less than $\sim 0.7\lambda$, then the resulting array patterns associated with each subchannel will consist of the narrow beams with low sidelobes, yielding high directivity and thereby tending to improve the SNR of each subchannel.

MIMO Arrays with Small Spacings: The deleterious effect of shortened element spacings – typically of interest so as to produce the smallest possible arrays – is essentially the same for MIMO as it is for rank-1 problems. However, the analysis is more complex and the specific role of coupling in MIMO arrays has emerged as a controversial issue in recent years. It is well known that coupling has two relevant effects: (1) modification of the impedance presented at the element terminals, and (2) modification of the pattern of the elements [7]. If the system is designed under the assumption that the antenna will present a standard (e.g., 50Ω) impedance, then the impedance modification will certainly degrade the aggregate radiation efficiency of the array, which in turn will degrade subchannel SNR and hence capacity for a given transmit power. However, there is also evidence that coupling due to spacings less than $\lambda/4$ *directly* degrades diversity order [18]. This specific effect can be reduced – but not completely mitigated – through optimized impedance matching for spacings down to $\sim 0.1\lambda$. However, it is well known that an optimized impedance match may not yield the best overall SNR in complete systems, once the contribution of low-noise amplifiers to SNR is taken into account [19]. In fact, evidence exists that *noise-optimized* matching may yield superior capacity for spacings greater than 0.1λ [20]. Thus, considerable care is required in designing arrays with spacings less than the $\sqrt{A_e}$ criterion, and in these cases the use of a complete system model such as [20] or [21] is strongly recommended for design verification.

Coupling-Induced Pattern Diversity: Concerning the modification of the element patterns as the result of coupling, it has been pointed out that this may have a positive impact on capacity by creating a degree of pattern diversity: Since different elements will be sensitive to different fields of view, they will tend to experience decreased correlation if the angle spread is large enough [22]. However, the actual benefit is different for rank-1 diversity, rank-1 beamforming, and MIMO. From a diversity perspective, this effect is almost certainly helpful; whereas for beamforming, the effect is almost certainly unhelpful. Since MIMO subchannels may use either or both of these approaches, the advantage is unclear. Whereas pattern diversity is likely to contribute to an increase in *rank*, *capacity* increase is possible only if the associated subchannels exhibit comparable instantaneous SNRs. Furthermore, gains due to increase in rank may be offset to some degree by the degraded radiation efficiency associated with coupling, identified above. In [23], it is suggested that radiation efficiency offsets the benefit of pattern diversity in monopole arrays in large angle spread, leading to capacity that is roughly independent of element spacing for spacings as short as 0.2λ. Other studies have indicated that capacity steadily declines for spacings less $\sim \lambda/3$ due to an overwhelming reduction in radiation efficiency [21], [24], [25].

Alternative Element Types: Finally, it should be noted that a number of innovative MIMO antenna systems have been proposed that transcend the "array of wire antennas" paradigm implicit in the above discussion. These include switched parasitic antennas [26], compact multimode antennas [27], [28], and the "MIMO cube" [29]. Space limitations preclude a proper discussion of these design concepts here.

VI. Site Planning Considerations

A number of site planning considerations have already been identified above: For example, choosing between linear and rotationally-symmetric arrays depending on the nature of the angle spread, and choosing between diversity and beamforming configurations depending on SNR. This paper concludes with consideration of array design for hallways, which are a ubiquitous feature of the indoor "terrain" and are already known to be prone to rank collapse [30].

The hallway problem can be described briefly as follows: Recall from Section II that most building spaces can often be characterized in terms of generally conductive floors and ceilings and interior walls which are essentially lossy dielectric. In hallways, at least one wall is "missing," which promotes propagation in that direction. From an electromagnetic perspective, the hallway behaves very much like a parallel plate waveguide formed by the floor and ceiling, with rough, lossy dielectric walls formed by the sides of the hallway. Since the cross-section of the hallway is electrically large, it supports not only the zero-order transverse electromagnetic (TEM) mode, but also 10s to 100s of higher-order modes. These modes can be interpreted as plane waves which bounce between walls, and between floor and ceiling, in a periodic fashion. As these modes propagate along the hallway, the interruptions in the otherwise-smooth surfaces – such as doors, wall hangings, or plumbing – result in transfer of power from lower-order modes into higher-order modes. At the same time, the higher-order modes experience greater attenuation as they travel along the hallway because the effective path length (that is, the length of the path traversed by zig-zagging plane waves) is longer, allowing power to exit the hallway laterally (into rooms) at a greater rate. As a result, a few of the lowest-order modes soon dominate. Since the phase statistics of these modes are highly correlated, the resulting channel tends toward a keyhole condition ($k_e \sim 1$). It appears that this can happen within 10s of meters [30], and once rank collapse has occurred, it cannot be restored even if signal power is diverted into a room and scattered again after this point.

Thus, if channel rank is to be maintained, links requiring propagation over more than a few meters of hallway should be avoided. If this cannot be avoided, there is not much that can be done from the perspective of the design or placement of arrays deployed within rooms, since array designs which are suitable for good MIMO performance within rooms should already yield good rank-1 performance within rooms. To maintain MIMO channel rank within a hallway, access points may be required every 10 m or so with coverage areas adjusted so that no propagation path includes a length of hallway sufficiently long to experience rank collapse.

On the other hand, such extreme measures to maintain channel rank may not be warranted. The "silver lining" in hallway waveguiding is that propagation along the hallway is relatively less lossy than propagation between rooms. For this reason, there may actually be a net gain in capacity relative to a room-to-room link of comparable length. This effect has been identified in some field tests (e.g., [31]) but has probably been inadvertently suppressed in many others due to the common practice of normalizing capacity statistics to a standard SNR.[2] The problem of how to make informed choices between (1) maintaining full rank by using many access points with small coverage areas, and (2) allowing some degree of rank collapse and compensating with increased SNR, is an interesting one worthy of further investigation.

Another consequence of the hallway waveguiding phenomenon which is not widely known is that fading statistics in hallways may differ in the vertical and horizontal planes. Whereas the fading statistics in the horizontal plane tend to be Ricean (as expected), the fading statistics in the vertical plane tend to be more akin to two-ray fading if the floor and ceiling are efficient reflectors [32]. This occurs because (as explained above) the hallway encourages the dominance of just a few low-order modes having roughly equal signal strength and with highly correlated phase distributions. This leads to fading that is much worse than classical Rayleigh fading, which is the result of multipath with *uncorrelated* phase distributions. This effect can severely degrade the achievable SNR of an array confined to the horizontal plane, and yet is easy to overlook because it is not apparent until one varies the height of at least one end of the link, and only then if SNR normalization is not employed. For this reason, two-dimensional (i.e., *vertical* as well as horizontal) or vertical-only distributions of elements may be the best choice for arrays which terminate links involving long hallways.

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