A Review on MIMO Antennas Employing Diversity Techniques

Arny Adila Salwa Ali[1*], Sharlene Thiagarajah, PhD[1]

[1] *Telekom Research & Development Sdn. Bhd., Idea Tower, UPM-MTDC, Technology Incubation Center One, Lebuh Silikon, 43400 Serdang, Selangor, Malaysia.*

Multiple-input-multiple-output (MIMO) technology is a generic term used to describe techniques proposed to improve capacity, bandwidth efficiency or data rates for the next generation wireless communication systems. MIMO systems integrate multiple antenna elements with adaptive signal processing to provide smart array processing, diversity combining or spatial multiplexing capability. The performance of a MIMO system depends on the correlation properties of its multipath signal. Low correlation between multipath signals is desired to improve channel capacity. This is achieved by exploiting antenna elements that can provide diversity via its spatial configuration, polarization potential or radiation pattern characteristics. This paper shall provide a review of the various MIMO antenna designs that focuses on spatial, polarization and pattern diversity, and its impact on performance. Issues on size, cost and implementation complexity will also be highlighted.

1. Introduction

Recent studies have shown that the multiple input multiple output (MIMO) system is a promising solution to cater to the growing demands for a higher data rate, higher capacity and a more spectrum efficient wireless communications system [1-2]. A MIMO system uses multiple antennas or elements combined with adaptive signal processing at both transmitter and receiver to exploit the space-time dimensions of a rich multipath environment. This method has been shown to improve capacity over the conventional single input single output (SISO) systems [3]. MIMO capacity performance depends on the characterization of its channel matrix. The channel rank, which is equivalent to the number of uncorrelated channel path gains, linearly increases with capacity [4]. Best capacity performance is achieved when the channel matrix has full rank, which is a result of low correlation between the multipath signals.

Diversity techniques exploiting antenna properties such as array configuration, radiation pattern, polarization and multimode excitation can produce such desired result [5-7]. This has led to extensive work to design antennas that can optimize the MIMO system performance. Thus, the objective of this paper is to review the various antenna designs investigated for indoor and device level MIMO applications.

This paper is organized as follows; Section 2 gives an overview of the spatial, pattern and polarization diversity techniques and their influences on MIMO performance. Section 3 reviews the innovative antenna designs employing these diversity techniques. In this section, we highlight issues on size, cost, implementation complexity and its impact on performance. Finally, Section 4 concludes this paper.

2. Diversity Techniques for MIMO Systems

2.1 Spatial Diversity

In its simplest form, spatial diversity is achieved by using more than one antenna element at transmitter and/or receiver to increase the number of channel paths between TX-RX. With sufficient element spacing, correct number of elements, and appropriate array geometry or topology, signal quality over the wireless channel can be improved [8-14]. Adopting this scheme for MIMO, channel capacity can also be optimized. Fig. 1 shows the concept of spatial diversity with element spacing factor.

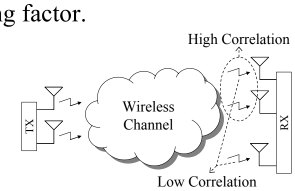

Figure 1: Spatial Diversity

As a rule, antenna element spacing should be a multiple of its frequency wavelength, to ensure independent fading on each element [7,9]. However, for small handheld devices like mobile phones and notebooks, size and cost constraints usually limit the full potential of spatial diversity. Insufficient spacing between antenna elements will cause mutual coupling between the elements, which will cause input impedance modification and pattern distortion to occur [15-17].

Combining an array system with space-time block coding (STBC) to form a smart adaptive selection of various element subsets (number of elements) can improve channel capacity or lower transmission error rate for actual MIMO systems in an unpredicted and volatile wireless environment [3,10], as opposed to fixed array systems that are usually designed based on theoretical propagation models.

2.2 Polarization Diversity

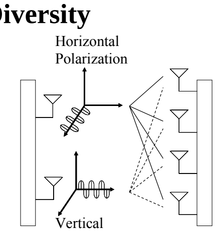

Figure 2: Polarization Diversity

Mutual coupling can be mitigated with the use of polarization diversity [18-19], which can be viewed as an extension of the space diversity scheme. In a typical case of linear polarization diversity, signals are transmitted and received via horizontally polarized as well as vertically polarized antennas, as illustrated in Fig. 2. The orthogonality

*E-mail: arny@tmrnd.com.my

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of two distinct polarizations constructs independent and uncorrelated signals on each antenna and thus, leads to potentially a full-rank MIMO channel.

Pairing vertically polarized TX and RX antennas is usually desirable for optimum performance since vertically polarized signals normally propagate slightly better than horizontally polarized signals [20]. Nevertheless, a MIMO system for indoor applications will suffer from cross-polarization induced by the highly reflective interior structures. This cross-polarization factor is a phenomenon where a signal is received with polarization that is orthogonal to the transmitted polarization [20].

Having multiple polarizations, with some antennas with horizontal polarization at both TX and RX antennas, would be a practical solution to cater to the indoor MIMO channel [21]. The option of using right-hand polarized and left-hand polarized antennas in the case of circular polarization would also help to decorrelate multipath signals more significantly, relative to the linear polarization case [22]. Array elements with circular polarization diversity can be designed to have minimal spacing to overcome any physical design limitation and have low spatial correlation, as the elements are electrically isolated due to different polarization orientation.

2.3 Pattern Diversity

Designing antennas with distinct radiation pattern, as shown in Fig. 3 for the case of array with two elements, constitutes the scheme of pattern diversity [23-25]. High correlation effect in a MIMO channel is minimized by taking advantage of the angle spacing of the TX and RX signals. With *angle diversity*, angle of departures of the TX signals or angle of arrivals of the RX signals are discriminated with the use of directional antennas pointing specifically to each angle direction. This ensures isolation between each TX or RX signals, and thus produces low correlation effect on the signals. Angle diversity is highly dominant when each of the antennas is able to receive the multipath signals from many different directions [26]. This causes the angle spacing to be narrowly spaced and thus generates high directivity due to the non-overlapping patterns. The highly orthogonal antenna patterns produce the desirable low correlated or uncorrelated MIMO signals. Small antennas, in comparison, tend to have overlapping omnidirectional patterns due to larger angle spacing causing high correlation impact on the MIMO channel [5].

Other method to guarantee high capacity performance in a MIMO system is to employ the exceptional technique of *multimode diversity*. This method exploits the characteristic of multimode antennas that exhibits orthogonal radiation patterns for different excitation modes. Moreover, a single multimode antenna which is excited with fundamental TEM modes, can offer the advantage of having multiple orthogonal patterns for low correlation effect while eliminating the need for multiple antenna elements as opposed to other diversity schemes [27-28]. It was presented in [28] that the biconical multimode antenna offers capacity gains similar to an array antenna for a MIMO scattering channel environment. Since the multimode antenna only requires a single element, it avoids the spatial requirements of an array and problems with calibration of the elements. Fig. 5 shows an example of radiation pattern in multimode diversity for a circular patch antenna [29]. It is also possible to have several different excitation modes at the same operating frequency on one antenna element, where the modes are then separated at different antenna ports [30].

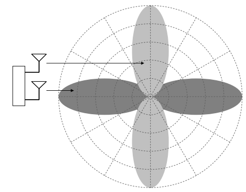

Figure 3: Pattern Diversity

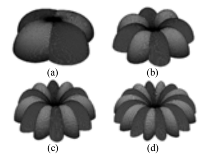

Figure 4: Four radiation patterns of circular patch antennas excited with different modes [29].

3. Antenna Designs for MIMO Systems

This section attempts to review various prominent antenna designs and the diversity techniques employed for MIMO. A summary of the various antenna elements used and its impact on performance is given in Table 1. In this section, we also investigate the effect of the antenna element on size, cost, implementation complexity and efficiency.

4. Conclusion

Based on the 46 papers reviewed, we can conclude that the dipole, monopole and patch antennas are the common choices for MIMO, mainly due to their small sizes. Spirals were the obvious choice for MIMO array systems due to their desirable pattern characteristics. However, practically, we found that spatial diversity schemes alone cannot mitigate size limitation issues or overcome the effects of mutual coupling completely. Thus, researchers began investigating polarization and pattern diversity schemes for the quest of more compact designs. Biconical antenna is one example that fits this requirement. Later, combinations of several diversity techniques were employed to significantly improve the MIMO capacity performance.

Spatial diversity technique was first investigated for MIMO antennas with low correlation between multiple antenna elements, and achieved using EMCP (electromagnetic coupled patch antenna) and the meandering patch method. Antenna designs with pattern diversity, polarization diversity, or any combination of the three diversity techniques was adopted to overcome the mutual coupling effect and improve MIMO channel capacity and bandwidth performance.

Multimode diversity, which is an enhancement of the pattern diversity technique, and the use of high dielectric constant materials are some of the other promising solutions currently investigated for MIMO. The mutual coupling problem is also tackled through use of smart antenna array techniques, such as the SPA and SMILE (spatial multiplexing of local elements [40]) techniques, with only a small increase in circuitry complexity and implementation cost. All these designs undoubtedly marked impression in the studies on antenna and promoted the evolution of the MIMO system for the next generation in wireless communications.

Table 1: Review Summary on MIMO Antenna Designs

Antenna Type	Diversity Technique	Size	Cost	Implementation Complexity	Performance Impact on MIMO
λ/2 dipole array [12, 31]	Spatial,	Small	Low	Simple	Higher capacity due to lower path losses & omnidirectional pattern
Two-arm spiral antennas [31]	Spatial	Medium	Low	Simple	Wider bandwidth & ±45° tilt azimuth patterns ideal for rich multipaths
Monopole array [32]	Spatial	Small	Low	Simple	Higher capacity due to lower path losses & omnidirectional pattern
Patch array [32]	Spatial	Small	Low	Simple	Higher capacity due to low correlation with sufficient spacing
Multilayer stacked dual-band patches array with U-shaped slots [33]	Spatial	Small	Moderate	Simple with EMCP [34]	Minimal spacing for low correlation, medium gain, wider bandwidth
Meander line printed quadrifilar helix antenna (MPQHA) [35]	Spatial	Small, compact	Moderate	Moderate due to meandering method	Higher capacity due to low correlation with advantage of more compact design
Modified meander line dual-band inverted-F arrays [36]	Spatial	Small, compact	Low	Moderate due to meandering method	Perfect for compact applications with higher throughput performance
Cube array of λ/4 wire elements [37]	Spatial	Small to Medium	Low	Simple	Low mutual coupling due to non-linear array gives higher capacity, advantage over Ricean fading
Tri-polarized compact array of 2-port patch antenna and 1-port λ/4-monopole [38]	Polarization	Small, compact	Low	Simple	Single element with three orthogonal polarization for low mutual coupling in rich multipaths
Compact microstrip slot based on SMILE techniques [39]	Spatial, Polarization	Small, compact	Moderate	Moderate due to multiplexing circuits [40]	Multiplexing enables polarization diversity in single RF, low correlation
Bi-polarized compact printed dipoles with integrated baluns [41]	Polarization	Small	Low	Simple with printed baluns	Low mutual coupling with orthogonal polarization
Modified double-folded dipoles with slab ceramic [42]	Polarization	Small, compact	Moderate	Simple	Low correlation, fit for handheld devices
Switched parasitic monopole array (SPA) [43]	Pattern	Small	Moderate	Moderate due to pattern switching diversity technique [44]	Smart angle diversity offers realistic capacity, joint use with STBC for higher data rates
Biconical antenna [30]	Polarization, Pattern	Small to Medium	Low	Simple	Single element with multimodes with low correlation for higher capacity
Self-complimentary, Archimedean four-arm spirals & Sinuous Antenna [45]	Polarization, Pattern	Small	Low	Simple	Single element with multimodes with wider bandwidth
Compact Inverted-F arrays [46]	Spatial, Polarization, Pattern	Small, compact	Low	Simple	Low correlation at small spacings for handheld devices

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