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Understanding Benefits Of MIMO Technology

Microwaves and RF

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Multiple antenna configurations can be used to overcome the detrimental effects of signal multipath and fading when trying to achieve high data throughput in limited-bandwidth channels.

Multiple-input, multiple-output (MIMO) antenna systems are used in modern wireless standards, including in IEEE 802.11n, 3GPP LTE, and mobile WiMAX systems. The technique supports enhanced data throughput even under conditions of interference, signal fading, and multipath. The demand for higher data rates over longer distances has been one of the primary motivations behind the development of MIMOorthogonal- frequency-division-multiplexing (OFDM) communications systems. For years, engineers assumed that the theoretical channel capacity limits were defined by the Shannon- Hartley theorem[1] illustrated in Eq. 1.

$$\text{Capacity} = \text{BW}\log_2(1 + \text{SNR}) \quad (1)$$

As Eq. 1 shows, an increase in a channel's SNR results in marginal gains in channel throughput. As a result, the traditional way to achieve higher data rates is by increasing the signal bandwidth. Unfortunately, increasing the signal bandwidth of a communications channel by increasing the symbol rate of a modulated carrier increases its susceptibility to multipath fading. For wide-bandwidth channels, one partial solution to solving the multipath challenge is to use a series of narrowband overlapping subcarriers. Not only does the use of overlapping OFDM subcarriers improve spectral efficiency, but the lower symbol rates used by narrowband subcarriers reduces the impact of multipath signal products.

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MIMO communications channels provide an interesting solution to the multipath challenge by requiring multiple signal paths. In effect, MIMO systems use a combination of multiple antennas and multiple signal paths to gain knowledge of the communications channel. By using the spatial dimension of a communications link, MIMO systems can achieve significantly higher data rates than traditional single-input, single-output (SISO) channels.[2] In a 2 x 2 MIMO system (***Fig. 1***), signals propagate along multiple paths from the transmitter to the receiver antennas.

Using this channel knowledge, a receiver can recover independent streams from each of the transmitter's antennas. A 2 x 2 MIMO system produces two spatial streams to effectively double the maximum data rate of what might be achieved in a traditional 1 x 1 SISO communications channel.

While research[3-7] has produced multiple methods to approximate the maximum channel capacity of a MIMO system, the channel capacity can be estimated as a function of N spatial streams. A basic approximation of MIMO channel capacity is a function of spatial streams, bandwidth, and signal-to-noise ratio (SNR) and is shown in Eq. 2:

Capacity = N BW $\log_2$ (1 + SNR) (2)

Given the equation for MIMO channel capacity, it is possible to investigate the relationship between the number of spatial streams and the throughput of various implementations of SISO and MIMO configurations. As an example, the IEEE 802.11g specs prescribe that a wireless-local-area-network (WLAN) channel uses a SISO configuration. With this standard, the maximum coded data rate of 54 Mb/s requires use of a 64-QAM modulation scheme[8] and a code rate of 3/4. As a result, the uncoded bit rate is 72 Mb/s (4/3 x 54 Mb/s). With minimum transmitter error vector magnitude (EVM) at -25 dB, an SNR of 25 dB can be estimated as the requirement for a 64-state quadrature-amplitude-modulation (64QAM) scheme. While EVM and SNR are not equivalent in all cases, we can assume that the magnitude error of a symbol will dominate the signal error as the SNR approaches its lower limit.

The maximum data rate of IEEE 802.11g maps closely with the maximum channel capacity dictated by the Shannon- Hartley theorem. According to this theorem, a Gaussian channel with an SNR of 25 dB should produce an uncoded data rate of 94 Mb/s in a 20-MHz channel bandwidth. Thus, the SISO implementation of IEEE 802.11g approaches, but does not exceed, the theoretical maximum channel capacity of the Shannon-Hartley theorem.

By contrast, Eq. 2 would suggest that a MIMO channel with four spatial streams should be capable of four times the capacity of the SISO channela 20-MHz channel with a signal-to-noise ratio (SNR) of 25 dB and four spatial streams should have an uncoded bit rate of 4 x 94 Mb/s = 376 Mb/s. This estimation maps closely with the expected data rates of the draft IEEE 802.11n physical layer specs.[9] IEEE 802.11n is designed to support MIMO configurations with as many as four spatial streams. At the highest data rate, bursts using a 64QAM modulation scheme with a 5/6 channel code rate produce a data rate of 288.9 Mb/s and an uncoded bit rate of 346.68 Mb/s. At the highest data rate, the IEEE 802.11n channel with four spatial streams produces a data rate that is comparable to the theoretical limit of 376 Mb/s. In Fig. 2, observe a comparison between the theoretical channel capacity of SISO and MIMO systems and the max. data rates (versus SNR) for IEEE 802.11g and IEEE 802.11n.

It can be observed that the bit rate of a 4 x 4 (four spatial stream) MIMO configuration exceeds that of the Shannon- Hartley limit at all data rates, making MIMO systems attractive for higher data throughput. While MIMO systems provide users with clear benefits at the application level, the design and test of MIMO devices is not without significant challenges. For example, MIMO systems require antenna designers to deal with the challenge of placing multiple antennas. Also, transceiver designers must solve the challenge of multi-channel synchronization. Finally, digital-signalprocessing (DSP) engineers are required to implement more sophisticated baseband processing algorithms to better interpret the channel model.

RF vector signal generators (VSGs) and vector signal analyzers (VSAs) are single-channel devices. The traditional three-stage superheterodyne architecture of RF vector signal analyzers does not lend itself to synchronization. For this reason, innovations from National Instruments and other vendors allow engineers to synchronize multiple VSAs and VSGs for phase-coherent RF acquisition and generation.

The requirement for multiple phasecoherent RF channels is dependent on the ability to share all clock signals between each up- or downconverter. Each channel of the MIMO test system uses a singlestage downconversion approach. In order for each acquired baseband I/Q signal to be phase-coherent, it is necessary to share a common local oscillator (LO) and analog-to-digital-converter (ADC) sample clock between each channel. The phase of each channel can be precisely calibrated by adjusting the start phase of the digital downconverter (DDC).

System benefits such as improvements in data rate and resilience to multipath are likely to motivate continued development of MIMO-OFDM communications systems.

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