Doc. Code

WLAN MIMO

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Contents

1 Overview

1.1 Definition

The multiple-input and multiple-output (MIMO) technology is introduced in the IEEE 802.11n protocol and brings the wireless local area network (WLAN) technology into a multi-antenna era.

Multiple antennas are used at both the transmit end and the receive end to transmit and receive signals. The MIMO technology reduces error codes and speeds up data transmission to improve service quality.

1.2 Purpose

In a traditional WLAN system, both an AP and a user device use only one antenna. Signals are transmitted through the 802.11a/b/g protocol. The maximum signal transmission rate is 54 Mbit/s and can hardly be increased anymore. With the increasing popularity and application of the WLAN technology, the rate of wireless communication needs to be increased substantially.

The MIMO technology, which is used in the 802.11n protocol, increases the rate of WLAN signal transmission greatly, and satisfies growing requirements on bandwidth and signal quality.

2 Principles

2.1 MIMO Technology

2.1.1 History

The MIMO technology is a breakthrough of the smart antenna technology in the field of wireless mobile communications. The MIMO technology increases the channel capacity and spectrum efficiency by multiple without changing the bandwidth. It is a key technology in new-generation mobile communications systems.

What is the history of the MIMO technology?

The MIMO technology has a long history dating back to 1908 when Marconi first used it to reduce fading. In the 1970s, the MIMO technology was recommended in communications systems. In the 1990s, scientists in the AT&T Bell Laboratories laid a foundation for the application of MIMO in wireless mobile communications systems.

In 1995, Telatar analyzed MIMO capacity in a fading environment. In 1996, Foschini proposed a new MIMO processing algorithm Diagonal-Bell Laboratories Layered Space-Time (D-BLAST). In 1998, Tarokh analyzed space-time codes for high data rate wireless communication in his paper composed together with other two scholars. In 1998, Wolniansky and other scientists established a MIMO experimental system using Vertical-Bell Laboratories Layered Space-Time (V-BLAST).

In an indoor experiment, a spectrum utilization of 20 bit/Hz was achieved. The 20 bit/Hz spectrum utilization was hard to achieve in common communications systems. The preceding work attracted worldwide attention and promoted the fast development of the MIMO technology.

2.1.2 MIMO Principles

In traditional WLAN communications systems, both an AP end and a user end use only one antenna. The antenna system is named single-input and single-output system (SISO). C.E.Shannon proposed the following formula to calculate channel capacity in a SISO system.

$$C = B*\log_2 (1 + S/N)$$

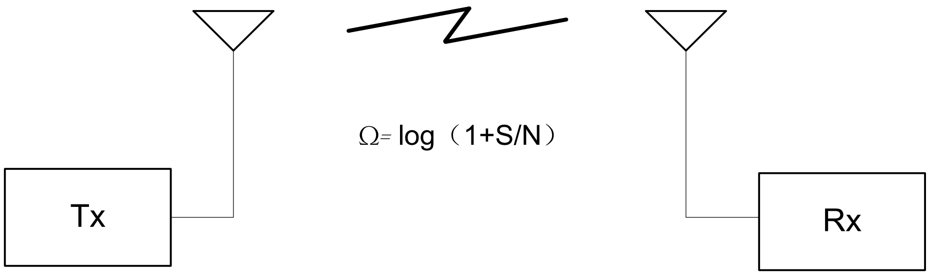
In the preceding formula, B stands for bandwidth of a channel and S/N stands for signal-to-noise-ratio.

The formula for bandwidth utilization is as follows:

$\Omega = \log_2 (1 + S/N)$

The preceding formula calculates the maximum rate of reliable communication in a channel with noises. Other technologies cannot provide a rate larger than the maximum rate no matter what modulation methods and channel coding methods are used.

Figure 2-1 SISO wireless channel system

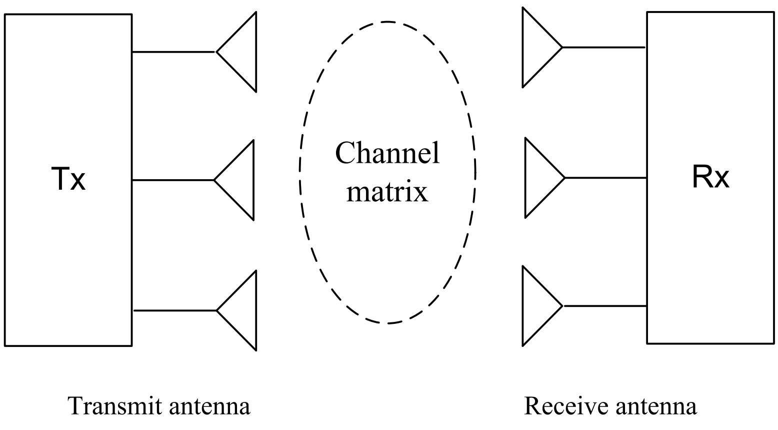


Install multiple antennas at the transmit or receive end. The antennas are considered independent of each other when antennas are far away from each other. Multiple independent channels are therefore constructed at the transmit or receive end. If a transmit end has N transmit antennas, a receive end has M receive antennas, and each stream of the M x N data streams are independent of each other in a wireless link, the system capacity increases with the number of antennas according to the information theory. In a MIMO system, the channel capacity can be calculated using the following formula:

$C \approx \min(M,N) * \log_2 (1 + S/N)$

As shown in the formula, under ideal conditions, if the number of antennas is not limited, a MIMO system can provide infinite channel capacity.

Figure 2-2 MIMO wireless channel system



As shown in Figure 2-2, a MIMO system contains N transmit antennas and M receive antennas. The transmit data stream is divided into N substreams, and is transmitted through N antennas at the same time after modulation. Through scattering transmission in wireless channels, the parallel substreams are transmitted to the receiver from different paths and are received by M receive antennas. The receiver processes the substreams and restores the original data stream.

Compared with traditional antenna systems, MIMO wireless communications systems transmit signals in multiple paths and construct multiple parallel transmission channels. Using the space-time block coding (STBC) technique, MIMO achieves transmit adversity and receive adversity, provides spatial multiplexing gain and spatial diversity gain, and improves channel capacity through parallel transmission channels. The MIMO technology is the most promising technology among emerging wireless communication technologies, and creates a significant way to high-speed transmission in wireless communications systems.

Note that in the MIMO technology:

The parallel N substreams are transmitted at the same time from the transmit end. All transmit signals use the same bandwidth and no extra bandwidth is needed, improving available bandwidth. Therefore, the MIMO technology maintains the total transmit power of the transmit end, achieves best power allocation without increasing the transmit power of the system.

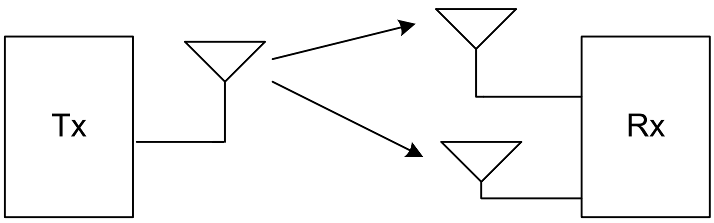
2.2 Spatial Diversity

MIMO provides two mainstream technologies for wireless channels: receive diversity and transmit diversity.

2.2.1 Receive Diversity

In receive diversity, the receiver uses more antennas than the transmitter (M > N). If the transmitter uses only one antenna (N = 1), the receive diversity is called SIMO. The following figure shows the simplest receive diversity that uses two receive antennas and one transmit antenna (SIMO, 1x2).

Figure 2-3 SIMO antenna configuration

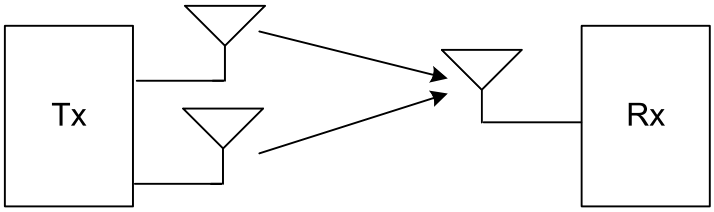


SIMO requires no special coding technique and is easy to implement. The receiver needs only two radio channels for receiving two independent loss signals transmitted. The signal noise ratio (SNR) of received signals can be increased using methods such as diversity selection and maximal ratio combining (MRC). Diversity selection presents the strongest signal, while MRC combines two signals.

2.2.2 Transmit Diversity

In transmit diversity, the transmitter uses more transmit antennas than the receiver (M < N). When the receiver uses only one antenna, the transmit diversity is called MISO. The following figure shows simplest transmit diversity that uses two transmit antennas and one receive antenna (MISO, 2x1).

Figure 2-4 MISO antenna configuration

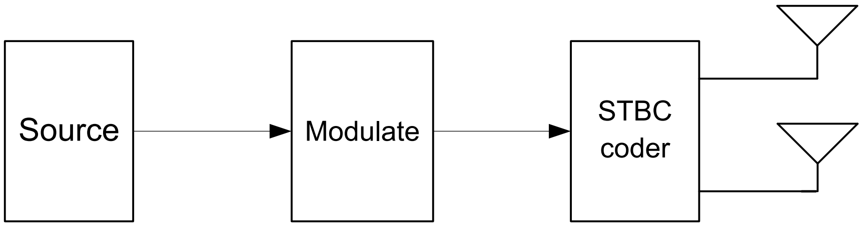


As shown in the figure, two antennas in the MISO system transmit corresponding data of the same signal. MISO uses the space time coding (STC) technology to improve the signal capability to prevent attenuation and increase the channel capacity.

STC integrates the characteristics of diversity, coding, and modulating. The most attractive feature of STC is that it achieves space division multiple access (SDMA) by combing coding and matrix technologies. This improves the capability of the system to prevent signal attenuation. In addition, STC provides high quality data transmission at high rate for the transmit and receive diversity. In contrast to the non-STC coding system, the STC system supports high coding gain while ensuring bandwidth, improving the anti-interference and anti-noise capabilities. WLAN 802.11n uses space-time block coding (STBC) technology. STBC is a simple and optional transmit diversity mechanism defined in 802.11n. It provides a diversity gain that amounts to the gain obtained through MRC. However, if the total transmit power is limited, STBC is not competitive because STBC provides a little gain. STBC enables a low-cost device that requires low power and low data transmission rate to obtain high link performance using the assigned wireless channels.

As shown in the preceding figure, STBC uses the Alamouti algorithm. Signals processed using orthogonal coding are transmitted over two antennas. These signals are transmitted independently and easy to differentiate at the receiver. Therefore, signals can be obtained by the receiver with only linear processing.

Figure 2-5 STBC implementation



The preceding figure shows the STBC implementation. The binary bit information sent from the source is modulated to $M = 2^m$ symbols. STBC coder maps two continuous symbols to signal matrix based on the following formula:

$$X=\begin{bmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{bmatrix}$$

Signal [x_1, $-x_2^*$] and signal [x_2, x_1^*] are mutually orthogonal. In the first specified time slot, two signals in each group are transmitted simultaneously. The signal sent from antenna 1 is x_1 and the signal sent from antenna 2 is x_2. In the next time slot, signal $-x_2^*$ is sent from antenna 1 and signal x_1^* is sent from antenna 2.

The STBC using Alamouti algorithm has been applied to multiple-antenna systems. If STBC is used, the transmitter must inform the receiver that signals are processed using STBC so that the receiver can implement corresponding decoding on the received signals.

2.2.3 MISO and SIMO Gain Analysis

MISO and SIMO belong to MIMO antenna system. The MIMO capacity is calculated based on the following formula:

$$C \approx \min(M,N) * \log_2 (1+S/N)$$

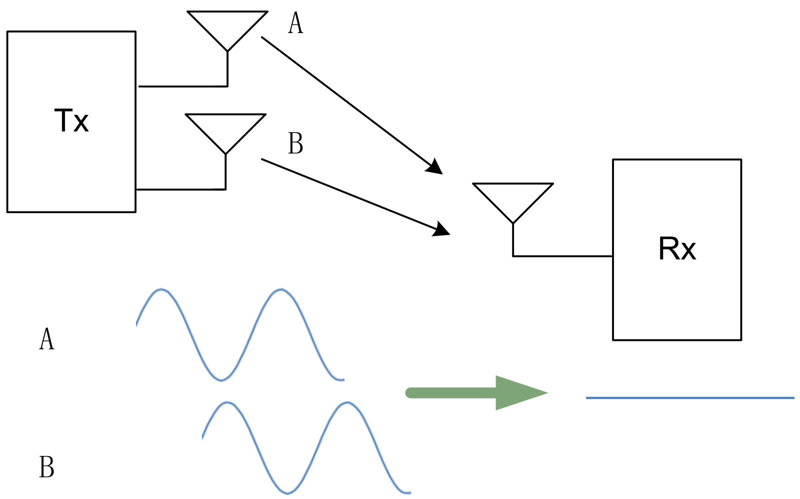
The increase of channel capacity depends on the minimum values of M and N. Therefore, the channel capacity is increased a little using SIMO and MISO.

Actually, the channel capacity provided by SIMO and MISO is slightly higher than that provided by SISO.

2.3 TxBF

What has been discussed above is the simultaneous transmission of the same signals in a multi-antenna system, which brings undesired space black holes. Each data copy is transmitted by a different antenna. After reaching the receive antenna through its specific path, each copy is reflected by different walls and devices. If two paths lead to the same location, whose signal loss is equal but phases are reversed, they will offset each other. A space black hole is therefore generated.

Reversed phases resulting in space black holes



However, effective transmit beamforming (TxBF) brings a completely different situation. If the phase of each path is compensated at the starting point of the transmit antenna, multiple data copies have the same phase when reaching the receive antennas. Instead of offsetting each other, two paths superpose with each other, improving transmission performance to the most. The auto-sensing TxBF described in the 802.11n standard refers exactly to this type of TxBF. It significantly improves the signal quality on the receive end.

2.3.1 TxBF Principles

TxBF facilitates reception by weighting transmission signals. The weighted coefficient is obtained based on the transmission environment and channel state information (CSI). Based on the method of obtaining transmitter weighting matrix, TxBF is classified into explicit beamforming and implicit beamforming.

Explicit Beamforming

Explicit beamforming is an optional mode defined in the 802.11n standard and requires the support of the client (receiver). In an explicit feedback mechanism, the TxBF STA is the STA that sends probe packets. STA A sends a detection packet to STA B, and STA B returns CSI or beamforming weight to STA A. According to this feedback, STA A sends a packet to STA B through TxBF.

Three explicit feedback formats are defined in the 802.11n standard: CSI, non-compressed beamforming weight, and compressed beamforming weight. The quantities of rows and columns in the CSI matrix and weight matrix respectively correspond to the number of antennas that receive detection packets and the HT-LTF quantity of the detection packets. If the TxBF transmit end has four antennas, the transmit hardware is required to send four spatial flows and the client (receiver) must support detection of four transmit antennas, while the mainstream chip currently supports only three antennas at most.

The explicit feedback, however, lowers the system efficiency. The 802.11n standard introduces quantization and subcarrier grouping technologies to bring down system costs.

The explicit beamforming provides the most precise information about channels. Once available (requires support of terminals), it can increase the throughput to the most and ensure link stability. Theoretically, the maximum possible beamforming gain on a flat channel is as follows:

$$G^{TxBF} = 10*\lg(Tx)$$

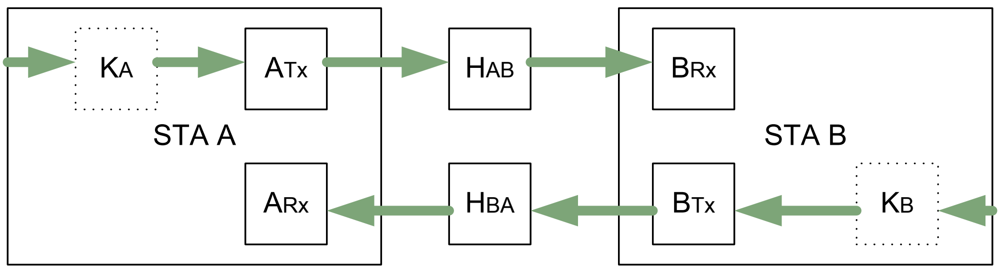
When there are three transmit antennas, the maximum BF gain is 4.77 dB; when there are four transmit antennas, the maximum BF gain is 6.02 dB, with an increase of 1.25 dB. The gain obtained in practice, however, is much lower. Measures designed to reduce system costs for feedback, such as quantization, subcarrier grouping, and compression, decrease the gain. In addition, the actual channel is frequency-selective rather than flat, so the effect of the beam convergence is limited. The channel environment changes with time, resulting in the feedback delay or the delay from measuring CSI to applying beams, which also degrades the channel performance. Therefore, compared to 3Tx, the practical gain of 4Tx increases only by a maximum of 0.75 dB.

Implicit Beamforming

Implicit beamforming is Cisco's ClientLink or ClientLink 2.0 that is a STA-free beamforming technology. An AP can measure the CSI of a channel at any time when STAs transmit signals. The CSI helps the AP return the data with least attenuation to STAs. It seems that this beamforming mode is free of STA limitations. This only tells part of the story.

Based on the electromagnetic equivalence principle, implicit beamforming allows transmit and receive beams on an antenna to use the same electromagnetic field. In the 802.11n standard, carriers with the same frequency are applied to two directions of a link. Ideally, the CSI measured on any end is the same when the coefficient affecting radios are equivalent on devices at both ends of the link. However, interference is not equivalent on the two ends. The channel between the digital basebands of devices includes the filter, power amplifier (PA), and low noise amplifier (LNA). The RF distortions of these devices are not equivalent.

The industry has been pondering on how to match transmit hardware and receive hardware of devices. The channel internal calibration solution is launched for high-end wireless devices, for example, LTE-TDD base station and WiMAX base station. This solution requires a control logic on the radio unit in addition to the coupler and power splitter. The cost and size exceed the allowed range for Wi-Fi. The 802.11n standard launched a STA-assisted calibration solution based on the low cost and small volume of Wi-Fi.



The calibration coefficient can be calculated as follows: STA A sends a probe packet to STA B so that STA B calculates the CSI H_{AB}. STA B then sends a probe packet to STA A so that STA A calculates the CSI H_{BA}. At the end of the switching of calibration packets, STA B sends the CSI H_{AB} to STA A. STA A obtains H_{AB} and H_{BA}, based on which STA A calculates the calibration coefficient K_A.

To help calibration, STAs need to support the calibration process as well as the number of antennas used in beamforming. If the TxBF transmit end has four antennas, the transmit hardware is required to send four spatial flows and the client (receiver) must support detection of four transmit antennas, while the mainstream chip currently supports only three antennas at most.

Some Wi-Fi device providers claim that their designs are independent of STA assistance on calibration. This is infeasible actually. The Wi-Fi features make it impossible to deploy radio calibration channels on the Wi-Fi radio board. The hardware match between transmit and receive devices can be accomplished only by integrating the transceiver on a chip. The Tx and Rx links must be configured the same on the chip. However, the channels of external radio components (such as PA and LNA) are independent, and consistency between their channels cannot be ensured. In addition, the RF distortions of active components may change inconsistently due to changes in the temperature in the current circuit, carrier frequency, or gain.

The RF channel consistency cannot be ensured if internal or external assistant calibration is not performed, which cannot ensure intentional beamforming. Unintentional beamforming cannot only provide required gains, but may also offset the signal gains.

To sum up, implicit beamforming applies to APs on a BSS network where at least a STA supports the assistant calibration function. The STA periodically help the AP perform calibration, and the calibrated AP can send intentional beamforming spatial streams to all 802.11n STAs regardless of whether they support beamforming and 802.11a/g STAs supporting only the single spatial stream on a BSS network. The increase in gains is to be tested in practice.

3 Summary

This document analyzes the MIMO technology in WLAN based on the Shannon's notion of channel capacity. The analysis result shows that the WLAN MIMO technology greatly improves the channel capacity and the increase of transmit and receive antennas helps improve system performance and reduce BER.

A single transmit or receive antenna contributes a little to increase in the system gain. How to obtain and leverage the CSI is to be researched.

In practice, a better choice is required for balance in addition to the system complexity and system performance.