[P. Papazian]

Demystifying MIMO

MIMO IS ONE OF THE HOTTEST TOPICS IN WIRELESS COMMUNICATIONS. WHAT'S BEHIND THE BUZZWORD?

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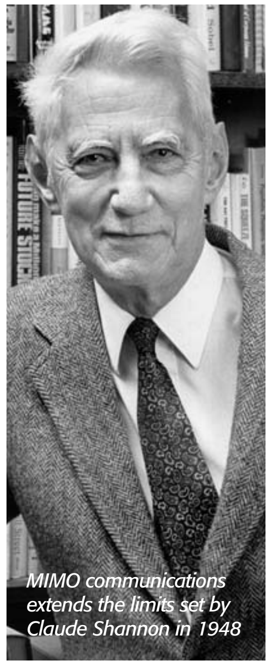
Since the publication of Claude Shannon's communications theory in 1948, researchers have been seeking ways of achieving and hopefully breaking his channel capacity limits. Traditionally, channel coding has provided the focus for these activities, where turbo and low density parity check codes are notable examples. Digital wireless communications often uses channel codes to improve link performance between a single transmitter and receiver. In the late 1990s, Telatar and Foschini independently proposed extensions to Shannon's capacity limits for wireless systems using multiple antennas at one or both ends of the link. These limits for multiple channels far exceeded those proposed by Shannon for a single antenna and stimulated intensive research to find ways of approaching these new bounds. Multiple-input multiple-output (MIMO) wireless communications was born.



MIMO communications extends the limits set by Claude Shannon in 1948

So what exactly is MIMO and how does it work? It's a buzzword. It's hot. It has something to do with spatial diversity and wireless LANs. It is often thought to be highly complex and power hungry (after all, you don't get something for nothing!). Here, we aim to explain what is behind the buzzword and how it relates to spatial diversity and WLANs.

The motivation behind MIMO has been the continued demand for capacity that is driven by the convergence of mobile phones, the Internet and multimedia services. Working against this demand is radio spectrum availability which determines the value of spectrum and transmission. Hence, methods that reduce the overall cost of transmission are highly sought after. Thus, for a given bandwidth, MIMO promises to improve the bit-error rate and/or data throughput. For example, a wireless system with four transmit and four receive antennas operating in ideal propagation conditions, i.e., with lots of multipath, and with a signal-to-noise ratio of 12 dB at 10% channel outage has a spectral efficiency of 11b/s/Hz. In comparison, a single antenna system requires 2048 constellation points and an SNR of more than 33 dB to achieve the same spectral efficiency. The spectral efficiency of MIMO grows linearly as the number of antennas increases, compared to logarithmic growth for systems with multiple antennas only at one end of the link. The aim, therefore, is to build a multiple antenna system in which as many as possible of the transmit and receive antenna-pairs are able to carry independent information channels within the same bandwidth. The system needs to be able to distinguish the information channels sharing the band.

SPATIAL DIVERSITY

Unlike many wireless technologies that aim to mitigate the effects of multipath propagation, MIMO can exploit it. Indeed, without multipath propagation, MIMO would, in general, not show any benefit. So how does MIMO work? Let's recap spatial diversity where several antennas are used at the receiver. Fading will occur at each antenna and varies with time. It is hoped that, while one antenna is in a fade, the other is not, as shown in fig 1. By selecting the antenna that is not in a fade, the system performance is improved (the availability of the channel has increased). This can be extended to the transmitter, selecting the transmit antenna(s) providing the best performance. This, however, requires the receiver to report its performance to the transmitter. Instead, by letting the transmitter use all its antennas simultaneously, feedback is avoided and more spatial paths between the transmitter and receiver are invoked. With many independent routes available for the signal to arrive at the receiver, a means of exploitation is required that provides a performance improvement above that of diversity gain. This spurred research into novel channel coding schemes to exploit spatial diversity provided by the transmitter, i.e. space-time codes (using space and time to construct the channel independence). Early transmit diversity schemes inserted a delay between antennas – delay diversity (sending slightly delayed copies of the same signal from different antennas). Delay diversity did not provide any coding gain and required a highly complex receiver. Note that polarisation diversity can be used instead of space (the gains here are easier to visualise). As long as the propagation supports this, the use of polarisation for two- or three-branch diversity makes a compact antenna array possible.

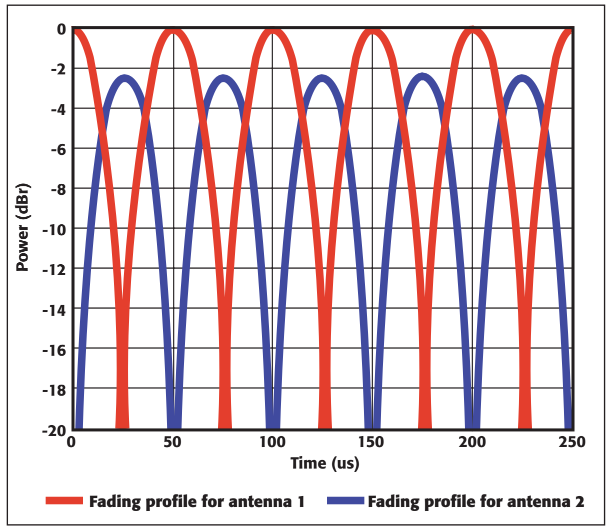


Fig 1. Explaining the concept of spatial diversity

SPACE-TIME CODES

One of the first researchers to publish a space-time code was S. Alamouti. His block code was for two transmit antennas and required only a small amount of additional processing at the transmitter and receiver. The receiver was considerably simpler than that required for delay diversity. Table 1 shows the required signal-to-noise ratio of Alamouti's space-time code to achieve a bit-error rate of 10^{-3} for various antenna combinations, binary phase shift keying and non-line-of-sight propagation in an urban environment. The power efficiency of the Alamouti code is always 3dB less than optimal receive diversity. This is due to each transmit antenna radiating half the energy of a single transmit antenna system.

Siavash M. Alamouti, Intel Fellow, Mobility Wireless Group, Intel Corporation, was one of the first to publish a space-time code

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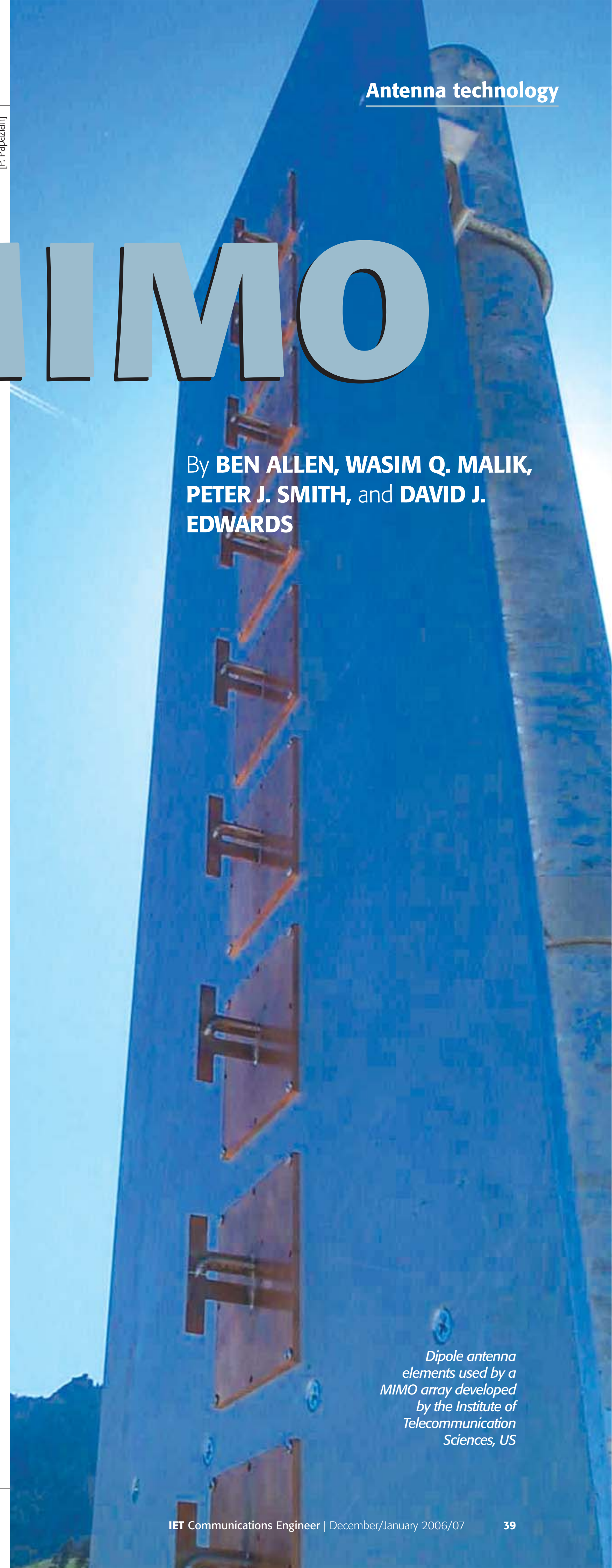


Dipole antenna elements used by a MIMO array developed by the Institute of Telecommunication Sciences, US

Antenna configuration	SNR required for BER=10^{-3}
No diversity (1 Tx, 1 Rx)	24dB
Alamouti (2 Tx, 1 Rx)	14dB
Optimal Rx diversity (1Tx, 2 Rx)	11dB
Alamouti (2 Tx, 2 Rx)	7dB
Optimal Rx diversity (1Tx, 4 Rx)	4dB

Table 1. Performance of Alamouti's space-time block code.

The Alamouti code was generalised by Tarokh, Jafarkhani and Calderbank to operate over an arbitrary number of transmit antennas. Unlike space-time trellis codes introduced later, their scheme, like Alamouti's, does not provide a coding gain; but, compared to previously proposed schemes, only simple linear processing is required. The difference between the generalised codes and Alamouti's code is that these codes incur a drop in spectral efficiency due to a reduction in coding rate. Spectral efficiency can be recovered by using Jafarkani's space-time block codes, where he trades off spectral efficiency for a reduction in diversity performance.

Just before Alamouti's code was published, Tarokh, Seshadri and Calderbank proposed space-time trellis codes which are akin to convolutional channel codes. These codes provide the same diversity performance as Alamouti's and Tarokh's space-time block codes and they also have coding gain therefore improving performance further. Decoding is, however, more complex but space-time trellis codes do yield very high spectral efficiencies.

The space-time codes discussed so far have required coherent QAM modulation. What if the system uses another modulation scheme? Tarokh and Jafarkhani proposed a differential detection scheme for their space-time block codes. As for single antenna differential modulation schemes, these codes require an additional 3 dB signal-to-noise ratio to retain the same bit-error rate achieved for coherent modulation. Hochwald and Sweldens proposed an alternative differential space-time block code that only has a 2dB performance penalty and can be adapted for an arbitrary number of transmit antennas, thus providing a power efficient improvement and greater design flexibility. At around the same time Hughes proposed an optimal code for two transmit antennas with a lower complexity decoder. Since differential demodulation does not require pilot signals, the increased SNR requirement can be traded off against the increased spectral efficiency obtained through eliminating the pilot signal overhead.

Can space-time codes be applied to MSK-modulated systems such as GSM networks? J Cavers has proposed a family of such codes. His codes are similar, yet simpler, and require less computational complexity than space-time trellis codes for QPSK and yield a comparable performance. Leus et al also proposed a space-time block code for power efficient modulation schemes. Their code is similar to Hochwald and Sweden's, except it has been tailored for non-coherent FSK modulation, making it very useful for power limited systems such as military and satellite communications. Similarly, Ho, Zhang and Kam have proposed Alamouti-type space-time block codes for coherent FSK modulation. Consequently, space-time codes are available for the majority of popular modulation schemes.

ENHANCEMENTS

Most of the above space-time coding schemes operate with an arbitrary number of transmit and receive antennas. Spatial multiplexing, proposed by Bell Labs, requires the number of receive-antennas to be at least as many as transmit-antennas. This is arguably true MIMO operation compared to multiple-input single-output (MISO) operation supported by space-time codes. Spatial multiplexing usually sends a number of independent data streams between the arrays, hence enormous data rates can be achieved. Advanced signal processing is required at the receiver to separate out the signals. The techniques are akin to those used for multiuser detection.

The signalling schemes described so far have all been for narrowband systems. In order to accommodate the convergence of multimedia and wireless communications, system designers are considering the use of much wider bandwidths, which inevitably results in frequency selective fading channels. These systems are referred to as 'wideband' or 'broadband wireless systems'. How can these systems benefit from MIMO? In general, three wideband technologies are available:

1 Equalisation;
2 OFDM; and
3 DS-CDMA.

Equalisation requires very little modification to the narrowband transmissions (except for the reduced symbol time). The received signal is equalised in order to remove the inter-symbol interference. An *OFDM* system decomposes the high-rate data into a number of low-rate (and hence narrowband) channels by means of an IFFT at each transmitter and FFT at the receiver (in effect carrying the information on a "parallel ribbon cable" in the frequency domain). The space-time coded symbols can therefore be mapped across the transmitters (space) and then either in the time domain or frequency domain. Space-frequency coding is the preferred option since it avoids channel variations occurring between symbols (in time). After the FFT at the receiver the decoding is the same as for narrowband systems. *DS-CDMA* systems incorporate space-time coding by employing a linear combiner for each branch of the rake receiver therefore providing an equalisation and diversity combining function.

Before wrapping up our discussion on space-time codes, we will clarify the relationship between MIMO and traditional beamforming. MIMO systems exploit multipath and the antenna elements are spaced far enough apart to give sufficiently decorrelated fading profiles (showing that the effective channels are independent – or different routes are taken by the signal) as illustrated in fig 1. Conversely, traditional beamforming requires the antenna elements to be spaced by approximately half-wavelength such that a directional beam is formed and there is very little variation between the signals associated with each element. Traditional beamforming systems may be referred to as smart antennas because they can be configured to adjust to the prevailing signalling conditions. Most MIMO systems may be referred to as dumb antennas because they do not self-adjust as signal conditions change – although they are less sensitive to such changes. Adaptive MIMO architectures are also being considered. They can adaptively optimise for data rate and/or robustness, overall power etc.

IMPLEMENTATION

The claims relating to spectral efficiency are of little use unless MIMO wireless systems can be physically implemented. This implementation can be a multi-disciplinary activity, requiring RF, embedded electronics, signal processing and knowledge of systems design, antennas and propagation. An example architecture, as

[Intel]

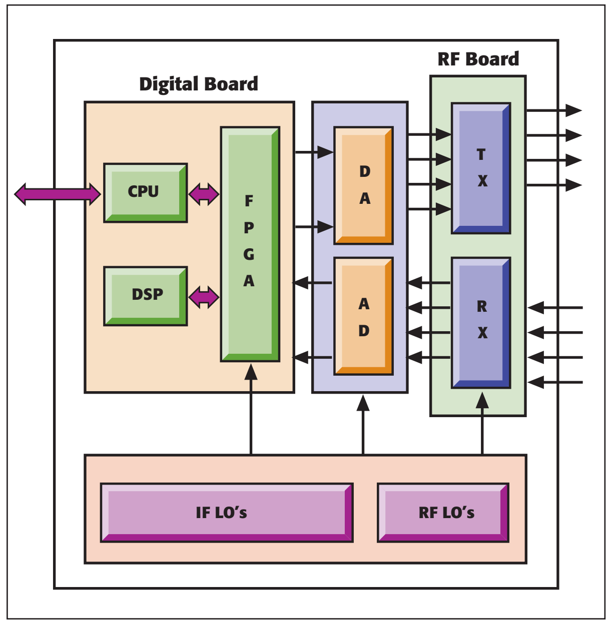
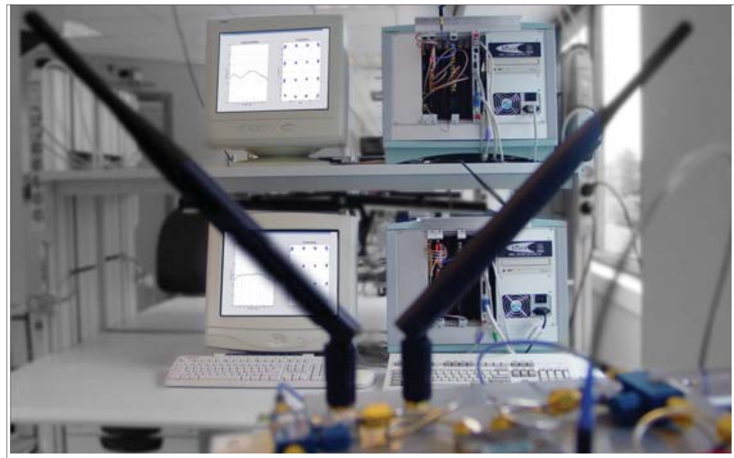


Fig 2. MIMO hardware architecture

shown in fig 2, shows a 4×4 transceiver, i.e. four up-converters and four down-converters. In the digital domain, processing can take place in an FPGA or for more intensive computation; the signals can be routed to a DSP. A CPU controls the system. The RF modules are fed with a common clock which ensures synchronisation between channels. Software is then executed to encode/decode the signals.

So, if the spectral efficiency of MIMO is so great, why isn't it deployed everywhere? There are some practical challenges that must be surmounted for successful →



[IMEC]

A MIMO prototype in the wireless lab at IMEC. The two terminals can be seen through the antennas of the access point.

implementation. Some of these are as follows.

1 Insufficient space is available to support multiple antennas, such as on a mobile handset;
2 Multiple receive/transmit chains require additional space and power;
3 Power constrains do not encourage the additional processing at the transmitter; and
4 The multipath propagation may be insufficient for a performance gain.

Despite these challenges, there are some notable applications of MIMO wireless as described below.

Netgear's RangeMax 240 wireless router for residential use uses MIMO technology. Netgear says the RangeMax 240 delivers speeds of up to 240 Mbps.

APPLICATIONS

Three well known applications of MIMO are in fixed wireless access networks (FWA); wireless LAN (WLAN) and third generation wireless systems (3G) systems. FWA provides a wireless broadband service and, by placing the antennas to below rooftop level, sufficient multipath is available to support MIMO operation. Since the units are stationary, system parameters relating to channel estimations can be relaxed. A topical example of a MIMO-enabled FWA system is Worldwide Interoperability for Microwave Access (WiMAX), also referred to as IEEE802.16. The WiMax physical layer is OFDM-based and can support the Alamouti space-time code as well as spatial multiplexing. The Alamouti scheme is touted to double the cell range while quadrupling the coverage and keeping the complexity at the basestation. Conversely, spatial multiplexing is used to double the data throughput at the expense of reduced range and power efficiency at the mobile unit.

A popular WLAN standard is specified by the IEEE802.11 committee. There are a multitude of variations, one of which, 802.11n, utilises MIMO-OFDM where spatial multiplexing is used as the MIMO signalling scheme. The goal is to achieve a very high data rate service – in excess of 100Mb/s – by exploiting the multipath-rich indoor propagation environment. Such WLANs are advertised as "MIMO-enabled" and the term even appears in consumer catalogues. Some early WLANs have implemented spatial diversity at the access point receiver to increase coverage.

Third-generation (3G) wireless systems are based upon a DS-CDMA air interface. Transmit diversity with two antennas may be implemented on the downlink as an option. Three modes of diversity are possible:

- Space-time block codes, i.e. the Alamouti code;
- Time switch transmit diversity where the transmit signal is switched from one antenna to the other; and
- Closed loop transmit diversity. Here, the signal is sent simultaneously from the two antennas and on different codes. Channel estimation takes place at the receiver and this is used to control the transmitter for optimum performance. This is akin to beamforming.

FUTURE EXPECTATIONS

So what can we expect for the future? Two possible applications under consideration are fourth generation and ultra-wideband wireless systems. MIMO is widely considered to be an integral technology to 4G, but it may be difficult to integrate multiple antennas into mobile terminals that are shrinking every year. Researchers are considering a new approach called 'virtual antenna arrays' or 'collaborative MIMO' as a solution. Here, terminals in the vicinity of the user are employed as elements of a virtual MIMO array and an additional short-range wireless link is established between the virtual elements.

Recently, ultra-wideband wireless systems have received much attention in the research community and show much promise in wireless multimedia and wireless sensor markets. Could MIMO further enhance UWB? The answer lies in wave propagation at these bandwidths. Since MIMO usually relies on multipath propagation for providing a capacity benefit, there has to be *diversity* available at the receiver even though many of the multipath components that enable diversity can be separated by the receiver due to the signal bandwidth. This does, however, depend on the bandwidth of the signal, since many UWB signals do not use all of the available bandwidth. Other factors such as antenna location and detector design also have to be considered. ■

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