Really Brief History of MIMO

ПРОБЛЕМЫ ПЕРЕДАЧИ ИНФОРМАЦИИ

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ПРОПУСКНАЯ СПОСОБНОСТЬ ВЕКТОРНОГО ГАУССОВСКОГО КАНАЛА БЕЗ ПАМЯТИ

Б. С. Цыбаков

Рассматривается канал связи с несколькими входами на передающем конце и несколькими выходами на приемном. Такой канал называется векторным. Описывается математическая модель дискретного по времени векторного канала, учитывающая интерференцию и фильтрацию входных сигналов и зависимость шумов на различных выходах. Отыскивается пропускная способность гауссовского векторного канала без памяти при весьма общем среднемощностном ограничении входных сигналов. Приводятся условия, в которых пропускная способность такого канала бесконечно велика.

Really Brief History of MIMO

THE CAPACITY OF A MEMORYLESS GAUSSIAN VECTOR CHANNEL

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Problemy Peredachi Informatsii, Vol. 1, No. 1, pp. 26-40, 1965 русский?

The author considers a so-called vector channel with several outputs at the receiving end and several inputs at the transmitting end. A mathematical model for a time-discrete vector channel is described with allowance for interference, filtering of input signals, and the relation between the noise values at the various outputs. The capacity of a memoryless Gaussian vector channel is found for very general average power constraints on the input signals. Conditions under which the capacity of such a channel is infinitely large are given.

Really Brief History of MIMO

Capacity of Multi-antenna Gaussian Channels

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Abstract

We investigate the use of multiple transmitting and/or receiving antennas for single user communications over the additive Gaussian channel with and without fading. We derive formulas for the capacities and error exponents of such channels, and describe computational procedures to evaluate such formulas. We show that the potential gains of such multi-antenna systems over single-antenna systems is rather large under independence assumptions for the fades and noises at different receiving antennas.

AT&T Bell Labs, Internal Tech. Memo, June 1995
(European Trans. Telecom., v.10, no. 6, Dec. 1999)

Really Brief History of MIMO

Wireless Personal Communications **6**: 311–335, 1998.

On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas

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Abstract. This paper is motivated by the need for fundamental understanding of ultimate limits of bandwidth efficient delivery of higher bit-rates in digital wireless communications and to also begin to look into how these limits might be approached. We examine exploitation of multi-element array (MEA) technology, that is processing the spatial dimension (not just the time dimension) to improve wireless capacities in certain applications. Specifically, we present some basic information theory results that promise great advantages of using MEAs in wireless LANs and building to building wireless communication links. We explore the important case when the channel characteristic is not available at the transmitter but the receiver knows (tracks) the characteristic which is subject to Rayleigh fading. Fixing the overall transmitted power, we express the capacity offered by MEA technology and we see how the capacity scales with increasing SNR for a large but practical number, n, of antenna elements at *both* transmitter and receiver.

Really Brief History of MIMO

IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 46, NO. 3, MARCH 1998 357

Spatio-Temporal Coding for Wireless Communication

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***Abstract*—Multipath signal propagation has long been viewed as an impairment to reliable communication in wireless channels. This paper shows that the presence of multipath greatly improves achievable data rate if the appropriate communication structure is employed. A compact model is developed for the multiple-input multiple-output (MIMO) dispersive spatially selective wireless communication channel. The multivariate information capacity is analyzed. For high signal-to-noise ratio (SNR) conditions, the MIMO channel can exhibit a capacity slope in bits per decibel of power increase that is proportional to the minimum of the number multipath components, the number of input antennas, or the number of output antennas. This desirable result is contrasted with the lower capacity slope of the well-studied case with multiple antennas at only one side of the radio link. A spatio-temporal vector-coding (STVC) communication structure is suggested as a means for achieving MIMO channel capacity. The complexity**

linear MMSE vector transmission and reception filters for $M \times M$ channels with no excess bandwidth. More recent work on MIMO equalizers includes the linear equalizer with excess bandwidth and the decision feedback equalizer [5]–[7].

Consider the problem of communication with linear modulation in a frequency-dispersive spatially selective wireless channel $\boldsymbol{H}$ composed of M_T transmission antennas and M_R reception antennas with additive noise. What is the impact of multipath on the information capacity of the discrete time communication channel? How do various multiple antenna structures influence channel capacity? Is it possible to construct multiple antenna coding systems that benefit from the inherent properties of severe multipath channels? This paper

Really Brief History of MIMO

3590 IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 9, NO. 11, NOVEMBER 2010

Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas

Thomas L. Marzetta

***Abstract*—A cellular base station serves a multiplicity of single-antenna terminals over the same time-frequency interval. Time-division duplex operation combined with reverse-link pilots enables the base station to estimate the reciprocal forward- and reverse-link channels. The conjugate-transpose of the channel estimates are used as a linear precoder and combiner respectively on the forward and reverse links. Propagation, unknown to both terminals and base station, comprises fast fading, log-normal shadow fading, and geometric attenuation. In the limit of an infinite number of antennas a complete multi-cellular analysis, which accounts for inter-cellular interference and the overhead and errors associated with channel-state information, yields a number of mathematically exact conclusions and points to a desirable direction towards which cellular wireless could evolve. In particular the effects of uncorrelated noise and fast fading vanish, throughput and the number of terminals are independent of the size of the cells, spectral efficiency is independent of bandwidth, and the required transmitted energy per bit vanishes.**

point-to-point system, but are retained in the multi-user system provided the angular separation of the terminals exceeds the Rayleigh resolution of the array.

Channel-state information (CSI) plays a key role in a multi-user MIMO system. Forward-link data transmission requires that the base station know the forward channel, and reverse-link data transmission requires that the base station know the reverse channel.

A. Multi-user MIMO systems with very large antenna arrays

Multi-user MIMO operation with a large excess of base station antennas compared with terminals was advocated in [7] which considers a single-cell time-division duplex (TDD) scenario in which a time-slot over which the channel can be

Really Brief History of MIMO

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Massive MIMO Has Unlimited Capacity

Emil Björnson, *Member, IEEE*, Jakob Hoydis, *Member, IEEE*, and Luca Sanguinetti, *Senior Member, IEEE*

***Abstract*— The capacity of cellular networks can be improved by the unprecedented array gain and spatial multiplexing offered by Massive MIMO. Since its inception, the coherent interference caused by pilot contamination has been believed to create a finite capacity limit, as the number of antennas goes to infinity. In this paper, we prove that this is incorrect and an artifact from using simplistic channel models and suboptimal precoding/combining schemes. We show that with multicell MMSE precoding/combining and a tiny amount of spatial channel correlation or large-scale fading variations over the array, the capacity increases without bound as the number of antennas increases, even under pilot contamination. More precisely, the result holds when the channel covariance matrices of the contaminating users are asymptotically linearly independent, which is generally the case. If also the diagonals of the covariance matrices are linearly independent, it is sufficient to know these diagonals (and not the full covariance matrices) to achieve an unlimited asymptotic capacity.**

the transmit precoding in the downlink. Since the channel estimates are obtained by uplink pilot signaling and the pilot resources are limited by the channel coherence time, the same pilots must be reused in multiple cells. This leads to pilot contamination which has two main consequences: the channel estimation quality is reduced due to pilot interference and the channel estimate of a desired UE is correlated with the channels to the interfering UEs that use the same pilot. Marzetta showed in his seminal paper [1] that the interference from these UEs during data transmission is also reinforced by a factor M, under the assumptions of maximum ratio (MR) combining/precoding and independent and identically distributed (i.i.d.) Rayleigh fading channels. This means that pilot contamination creates a finite SE limit as $M \to \infty$.

- seriously ??? ☺