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EFFECTS OF SIGNALS CLUSTERING ON THE CAPACITY OF INDOOR MIMO CHANNELS

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1. Introduction

The multi-input multi-output (MIMO) technique incorporating space-time coding is a candidate for the next generation high performance wireless communication systems. The MIMO technique employs multiple-element antennas to establish spatial subchannels to improve spectrum efficiency. The promised increase in channel capacity by MIMO is possible only if rich-scattering is present in propagation environments. Theoretically, a narrow band MIMO channel with n_t transmit and n_r receive antennas is described in terms of an $n_r \times n_t$ complex channel matrix H, whose entry h_{ij} represents the channel impulse response between the ith receive antenna and the jth transmit antenna. The signal model of MIMO systems is represented as a matrix equation: $Y(t) = H(t)X(t) + N(t)$. The capacity of the MIMO channel with uniform-power-allocation scheme is given by [1, 2]:

$$C = \log_2 \det(I + \frac{\rho}{n_t} HH^*) \tag{1}$$

With ideal assumptions, the entries of H will be i.i.d circularly symmetric Gaussian random variables with zero mean and unit variance [1, 2]. In the literature, most MIMO channel models reconstruct the channel matrix from the spatial correlation point of view [3-5]. Although the stochastic model in [6] includes the indoor scenario, it does not consider the phenomena of clustering signals encountered in indoor environments [7, 8]. Accounting for the indoor clustering phenomena, a stochastic double directional channel model is introduced here which models the MIMO channel matrix directly based on a reference SISO channel impulse response. Using this model, we will investigate of the impact of clustering signals in indoor environments on MIMO performance.

2. Proposed Indoor Stochastic Double Directional MIMO Channel Model

A. Clustering SISO Indoor Channel Model –A Brief Review

The model used in this paper is based on the clustering SISO model which was proposed in [7, 8]. The SISO complex baseband impulse response of a multipath stationary indoor channel is represented as a linear combination of clustered multipath components

$$h(t) = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \beta_{ji} e^{j\varphi_{ji}} \delta(\theta - \theta_i - \omega_{ji}) \delta(t - T_i - \tau_{ji}) \tag{2}$$

where i is the number of clusters, j is the number of rays within i^{th} cluster. θ_i and T_i are the AOA and TOA of ith cluster. $\beta_{ji} e^{j\varphi_{ji}}$, ω_{ji} and τ_{ji} are the complex path gain and corresponding AOA and TOA of the jth ray within i^{th} cluster. The amplitude of each arrival is assumed to be Rayleigh distributed random variables and the mean square values follow a monotonically double-exponential decay function:

$$\overline{\beta_{ji}^2} = \overline{\beta^2(T_i, \tau_{ji})} = \overline{\beta^2(0,0)} e^{-T_i/\Gamma} e^{-\tau_{ji}/\gamma} \tag{3}$$

The power-delay time constant Γ of clusters, and γ for rays, are specific to the indoor environments. The associated phase shift of each arrival is generally assumed to be i.i.d uniformly distributed over [0, 2π). The time of arrival is described by two Poisson random variables: one represents the cluster arrival time, and the other, the arrival time of ray within clusters. Both are described by the independent inter-arrival exponential conditional probability density functions:

$$p(T_i|T_{i-1}) = \Lambda e^{-\Lambda(T_i - T_{i-1})} \quad \text{and} \quad p(\tau_{ji}|\tau_{(j-1)i}) = \lambda e^{-\lambda(\tau_{ji} - \tau_{(j-1)i})} \tag{4}$$

where Λ and λ are the arrival rate of clusters and rays within clusters, respectively. The TOA of clusters and TOA of rays are assumed to be statistically independent. The AOA of clusters is assigned to be a statistically uniform random variable over $[0, 2\pi)$[8]. The clusters were found to follow a zero-mean Laplacian PDF with the angle spreads of $22°$ and $26°$ in different indoor environments[8]. The cluster statistics (distribution of θ_i and T_i) are independent of the statistics of rays within clusters (distribution of τ_{ji} and ω_{ji}).

B. Number of Arrival Clusters and Rays

Most of the measurement results available in the literature regarding clustering phenomena indicate that the detectable clusters are limited. Thus, in our model, the numbers of incident clusters and rays within individual clusters are taken to be finite. Accounting for the mean number of clusters and rays within clusters, which both can be deduced experimentally, two Poisson processes are utilized to generate a discrete number of incident clusters, and rays within individual clusters.

$$N_c = P(\overline{N_c}) \qquad \text{and} \qquad N_i = P(\overline{N_i}) \tag{5}$$

where $P(x)$ is Poisson process with mean values x. $\overline{N_c}$ and $\overline{N_i}$ are the mean number of clusters and rays within each cluster.

C. Angle of Departure and Angle of Arrival

To simulate the indoor nonisotropic clustering scattering, the von Mises probability density function (PDF) is used to characterize the double directional indoor propagation channel [9]. The von Mises PDF for the angle θ, $p(\theta)$ is given as $p(\theta) = \exp[k\cos(\theta - \mu)]/2\pi I_0(k)$. where $I_0(k)$ is the modified Bessel function of the first kind and order zero, the parameter μ is the mean direction, and the parameter k determines angle spread. A uniform distribution is a special case of von Mises PDF when $k = 0$. To incorporate the double directional channels, we utilize two parameters, k_R and k_T, to characterize the AOA and AOD of clusters. k_R and k_T can be the same when both Tx and Rx are in the same indoor environment. They can be different when Tx and Rx are in different propagation environments. The AOA and AOD of rays within clusters, ω_{ji}^T and ω_{ji}^R, are also characterized by the von Mises PDF with parameters of k_{TC} and k_{RC}, respectively. It was found that when $k=21$, the von Mises PDF is comparable with the Laplacian distribution with an angle spread of $22°$.

D. The MIMO Channel Matrix

For the MEA systems, we assume that the antenna elements used at Tx and Rx are identical and all the elements of the Tx/Rx array are assumed to be within the same small-scale fading regime as that of their reference element respectively. Then, the channel established between the reference antennas allows the use of the SISO channel model introduced earlier with the extended equation (2) to include both AOA and AOD as:

$$h_{00}(t) = \sum_i^{N_c} h_{00,i}(t,\theta^T,\theta^R) = \sum_i^{N_c}\sum_j^{N_i} \beta_{ji} e^{j\varphi_{ji}} \delta(t - T_i - \tau_{ji})\delta(\theta^T - \theta_i^T - \omega_{ji}^T)\delta(\theta^R - \theta_i^R - \omega_{ji}^R) \tag{6}$$

where $h_{00,i}(t,\theta^T,\theta^R)$ is the induced response of the ith cluster with AOD of θ^T and AOA of θ^R, and other parameters are as in equation (2). With the assumption of the same small-scale fading regime, all the array elements should encounter the same propagation channel as their reference element. The MIMO channel matrix then is represented as a function of the reference SISO channel impulse response $h_{00}(t)$ as:

$$H(t) = [h_{ij}(t)]_{n_r \times n_t} = \sum_i^{N_c} (a_R(\theta))^T h_{00,i}(t,\theta^T,\theta^R) a_T(\theta) \tag{7}$$

where $a_R(\theta)$ and $a_T(\theta)$ are the response vectors of transmit and receive arrays respectively. They are of the form $a(\theta) = g_a(\theta) \cdot [1 \quad e^{-j2\pi d_1 \cos\theta/\lambda_0} \quad \cdots \quad e^{-j2\pi d_{M-1}\cos\theta/\lambda_0}]$ for M-element ULA.

3. Impact of Clustering Signals

In this section, the investigation of the impact of the clustering signals in indoor environments on the MIMO system in presented. The stochastic MIMO model used is validated by comparing with measurement results on channel capacity. Fig.1 shows a comparison between the proposed stochastic model and an indoor measurement results published in [10]. The simulated MIMO channel is established between two 4-element uniform linear arrays at 5.2 GHz with an SNR of 20 dB which is same as that used in measurements. There is considerable agreement between both which verified our model.

For the clustering indoor channel, the impact of both the number of incident clusters and rays within individual clusters are of most interest. However, from a practical point of view, both are not easy to obtain experimentally. Further, their impact is not well investigated as yet. With the stochastic model, based on the Monte Carlo simulation results shown in Fig.2, some insights can be gained. The macro parameter—the number of incident clusters influences the MIMO capacity significantly in the range up to 15 clusters. Beyond this range, the impact becomes very small. The micro parameter—the number of rays within each cluster seems to have little effect on the capacity. (Note that the number of rays in Fig.2 is four times the x-axis.) The reason for this can be two fold. Firstly, although the number of rays within each clusters increase; since they all are angularly spread around the AOA of the cluster, their impact on the spatial correlation does not change when there is a change in the number of rays. Secondly, the increase of incident clusters in a certain range influence the statistics of the correlated channel significantly as the increasing of incident clusters increases the angular spread of the channel. When the number of clusters becomes larger, the impact of the increase on the statistical property is very little.

The von Mises parameter k in the model represents the angular characteristic of the clustering signals. Fig.3 shows the angular impact of the clustering signal on the MIMO channel capacity. As we expect, both macro angular properties (k_R , k_T) and micro angular properties (k_{TC} , k_{RC}) of clusters influence the channel capacity. But the impact of the macro angular characteristic is much significant than that of the micro angular characteristic.

The temporal impact of clustering signal on the channel capacity can be found in Fig.4. In the histogram, it is clear that the rms delay spread of the channels follow the Gaussian distribution with a mean of 50.3 ns. The maximum mean capacity of 29.569 bits/s/Hz is found to appear in the channels with a mean rms delay spread of 42 ns. The decrease in capacity with increasing rms delay spread can be seen as well. The reason for this could be due to many arrivals with some of them having larger excess delays and smaller path gains which contribute little to the spatial subchannel gain and hence to capacity gain. For those channels for which the rms delay spread is very small and the capacity is also very small, it may be interpreted due to the presence of not-so-rich multipath phenomena. A shorter rms delay spread means that multipath components (MPCs) with high path gains arrive around the first arrival in both temporal and angular domain. Hence the spatial diversity of this channel is not as good as those channels with medium rms delay spreads.

4. Conclusions

Using a parametric stochastic indoor MIMO channel model, the impact of clustering signals on the MIMO performance is investigated. The investigation showed that the influence of the micro parameters, such as angle spread of clusters and the number of waves within individual cluster is not as significant as that of the macro parameters, such as AOA, AOD and the number of incident clusters. The later parameter affect the performance of MIMO channel significantly which one must consider during the development of indoor MIMO systems. Further, our study has indicated that the MIMO channel capacity does not only depend on the richness of multipath components. From the temporal point of view, both the richness of MPCs and the temporal characteristics of the propagation channel affect the MIMO channel capacity as well.

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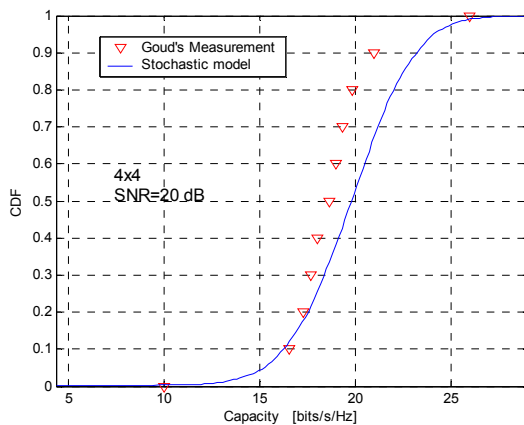
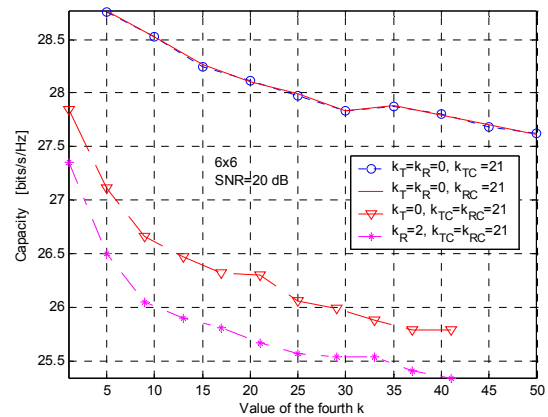Fig.1. Comparison of capacity of a 4x4 MIMO channel.

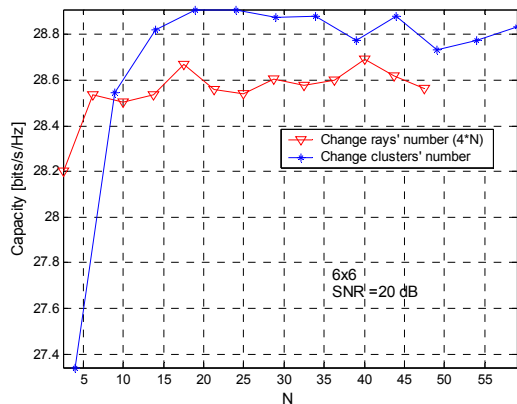Fig.3. Impact of angular property on channel capacity.

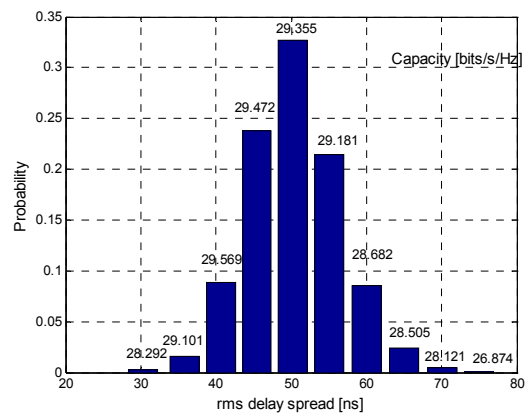Fig.2. Impact of number of clusters and rays within clusters on channel capacity.

Fig.4. Temporal effect on channel capacity.