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Estimation of Clustered MIMO Channel Parameters exploiting Channel Statistics

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Introduction

In addition to the sparsity property of a wireless channel, the channel multipath components are modeled as clusters of multirays due to scatterers distributed in the environment. This is a typical channel configuration that future multiple-input multiple-output (MIMO) wireless communication systems will have to cope with. Hence, there is a strong need to design new appropriate channel estimation techniques. A cluster of multirays can be characterized by its mean delay and its delay spreading. In a previous work, we have focused on estimating the mean delays of the different clusters based on a deterministic channel model. For the work to be complete, we propose in this work to estimate the standard deviation of the delay spreading of each cluster based on a stochastic model, exploiting time delays distribution of the scattered signals.

Channel model and system model

Consider an $N \times M$ MIMO system. For $n = 1 \dots N$ and $m = 1 \dots M$, the channel impulse response between the n th transmit antenna and the m th receive antenna can be modeled as:

$$h^{(n,m)}(t) = \sum_{l=1}^L \sum_{p=1}^{P_l} \alpha_{lp}^{(n,m)} \delta(t - (\tau_l^{(n,m)} + \tau_{lp}^{(n,m)})) \quad (1)$$

where $\delta(\cdot)$ is the Dirac function; L is the total number of propagation paths (clusters), with P_l contributing rays for the l th path (cluster), $\tau_l^{(n,m)} + \tau_{lp}^{(n,m)}$ is the p th contributing ray delay in the l th cluster with $\tau_{lp}^{(n,m)}$ a small deviation from the mean path delay $\tau_l^{(n,m)}$ and $\alpha_{lp}^{(n,m)}$ is the corresponding complex gain.

Pilot symbols on different carrier frequencies at each transmit antenna are sent through the channel in order to distinguish the paths between different transmit-receive antenna pairs. Suppose that a known pulse shape $g(t)$ is transmitted at a constant rate $1/T$. Signal contribution from the n th transmit antenna at the m th receive antenna is given as:

$$x^{(n,m)}(t) = \sum_{l=1}^L \sum_{p=1}^{P_l} \alpha_{lp}^{(n,m)} g(t - (\tau_l^{(n,m)} + \tau_{lp}^{(n,m)})) + z^{(n,m)}(t) \quad (2)$$

with $z^{(n,m)}(t)$ an additive white gaussian noise.

In this work, we assume that all multiray delays associated to a given scatterer l share a same distribution for different transmit-receive antenna pairs, having same mean delay with same variance of delay spreading. Hence in the above equation, $\tau_l^{(n,m)} = \tau_l$ where τ_l is the mean delay associated to cluster l .

Applying the discrete Fourier transform (DFT), the Fourier coefficients of the received signal are given by:

$$X^{(n,m)}[k] = \sum_{l=1}^L \sum_{p=1}^{P_l} \alpha_{lp}^{(n,m)} G[k] e^{-j2\pi k(\tau_l + \tau_{lp}^{(n,m)})} + Z^{(n,m)}[k] \quad (3)$$

for $k = -K/2 + 1, \dots, K/2$ where K is the considered number of Fourier coefficients, $G[k]$ is the DFT of pulse $g(t)$ and $Z^{(n,m)}[k]$ is the DFT of noise $z^{(n,m)}(t)$.

Let $v_k(\tau) = G[k] e^{-j2\pi k\tau}$, (3) can be rewritten as:

$$X^{(n,m)}[k] = \sum_{l=1}^L \sum_{p=1}^{P_l} \alpha_{lp}^{(n,m)} v_k(\tau_l + \tau_{lp}^{(n,m)}) + Z^{(n,m)}[k] \quad (4)$$

Channel parameter estimation

First, a deterministic model based approach is considered to estimate cluster mean delays.

As the delay deviations $\tau_{lp}^{(n,m)}$ are considered small, the U th order Taylor expansion of (4) gives:

$$X^{(n,m)}[k] = \sum_{l=1}^L \sum_{p=1}^{P_l} \alpha_{lp}^{(n,m)} (v_k(\tau_l) + \sum_{u=1}^U \frac{(\tau_{lp}^{(n,m)})^u}{u!} v_k^{(u)}(\tau_l) + R_U(\tau_{lp}^{(n,m)})) + Z^{(n,m)}[k] \quad (5)$$

where $v_k^{(u)}(\tau_l)$ is the u th order derivative of $v_k(\tau_l)$ and $R_U(\tau_{lp}^{(n,m)})$ is the remaining term in the Taylor approximation considered as small.

(5) can be approximated as:

$$X^{(n,m)}[k] \approx \sum_{l=1}^L \sum_{u=0}^U a_{l,u}^{(n,m)} v_k^{(u)}(\tau_l) + Z^{(n,m)}[k] \quad (6)$$

where $a_{l,u}^{(n,m)} = \sum_{p=1}^{P_l} \alpha_{lp}^{(n,m)} \frac{(\tau_{lp}^{(n,m)})^u}{u!}$.

The mean delays can be estimated, using the MUSIC-like method proposed in our previous work, by finding the locations of peaks of the following cost function:

$$P(\tau) = \frac{1}{\sum_{u=0}^U \mathbf{v}^{(u)}(\tau)^H \hat{\mathbf{U}}_n \hat{\mathbf{U}}_n^H \mathbf{v}^{(u)}(\tau)} \quad (7)$$

where

$$\mathbf{v}^{(u)}(\tau) = [v_{-K/2+1}^{(u)}(\tau), \dots, v_{K/2}^{(u)}(\tau)]^T$$

$$v_k^{(u)}(\tau) = (-j\frac{2\pi}{T}k)^u v_k(\tau) \quad (8)$$

and $\hat{\mathbf{U}}_n$ is the matrix of the estimated effective noise subspace eigenvectors.

As a second step, a stochastic model based approach is considered, where a stochastic channel model is derived, assuming a predefined statistical distribution for multiray delays. The Fourier coefficients for any transmit-receive antenna pair can be modeled with the following random function:

$$X[k] = \sum_{l=1}^L \int_{\tau \in \mathcal{T}} v_k(\tau) \alpha_l(\tau; \xi_l) d\tau + Z[k] \quad (9)$$

where \mathcal{T} is the interval in which the spreading for all clusters takes place; $\xi_l = [\tau_l, \sigma_l]$ is the parameter vector characterising the channel, such that τ_l is the mean delay and σ_l is the standard deviation of the delay spreading of cluster l ; $\alpha_l(\tau; \xi_l)$ is the complex gain in the cluster, where for a fixed ξ_l , $\alpha_l(\tau; \xi_l)$ is a random process with respect to the delay variable τ , and $Z[k]$ is the additive noise modeled as a gaussian random variable with zero mean and variance σ_z^2 . Since the gain coefficients are assumed to be identically distributed for all the transmit-receive antenna pairs with the same distribution of multiray delays, subscript (n, m) is omitted in the above equation.

The Fourier coefficients are concatenated to form the following random vector:

$$\mathbf{x} = \sum_{l=1}^L \int_{\tau \in \mathcal{T}} \mathbf{v}(\tau) \alpha_l(\tau; \xi_l) d\tau + \mathbf{z} \quad (10)$$

with $\mathbf{x} = [X[-K/2 + 1], \dots, X[K/2]]^T$ and $\mathbf{z} = [Z[-K/2 + 1], \dots, Z[K/2]]^T$.

The corresponding covariance matrix is given by

$$\mathbf{R}_x = E\{\mathbf{x}\mathbf{x}^H\} = \sum_{l,l'=1}^L \int_{\tau \in \mathcal{T}} \int_{\tau' \in \mathcal{T}} E\{\alpha_l(\tau; \xi_l) \alpha_{l'}^*(\tau'; \xi_{l'})\} \mathbf{v}(\tau) \mathbf{v}(\tau')^H d\tau d\tau' + \sigma_z^2 \mathbf{I} \quad (11)$$

where $*$ denotes the complex conjugate, and $\tau, \tau' \in \mathcal{T}$.

Assuming that the different clustered signals are uncorrelated, and the multirays within each cluster are also uncorrelated. It comes that :

$$E\{\alpha_l(\tau; \xi_l) \alpha_{l'}^*(\tau'; \xi_{l'})\} = \delta_{ll'} \delta_{\tau\tau'} \sigma_{\alpha_l}^2 w_l(\tau; \xi_l) \quad (12)$$

where δ_{pq} is the Kronecker delta.

The covariance matrix can then be written as follows:

$$\mathbf{R}_x = \sum_{l=1}^L \mathbf{R}(\tau_l, \sigma_l) + \sigma_z^2 \mathbf{I} \quad (13)$$

where

$$\mathbf{R}(\tau_l, \sigma_l) = \sigma_{\alpha_l}^2 \int_{-\infty}^{+\infty} w_l(\tau; \xi_l) \mathbf{v}(\tau) \mathbf{v}(\tau)^H d\tau \quad (14)$$

is the covariance matrix of the l th received clustered signal, $w_l(\tau; \xi_l)$ is the normalized power delay function of the cluster and $\sigma_{\alpha_l}^2$ is its total mean power.

Assuming that multiray delays in each cluster are uniformly distributed, we have,

$$[\mathbf{R}(\tau_l, \sigma_l)]_{k+K/2, k'+K/2} = |G[k]|^2 e^{-j2\pi(k-k')\tau_l} \text{sinc}\left(\frac{2\pi}{T}(k-k')\sqrt{3}\sigma_l\right) \quad (15)$$

For the clustered signal l , we have:

$$\mathbf{R}(\tau_l, \sigma_l) \mathbf{U}_n = \mathbf{0} \quad (16)$$

Hence the proposed scheme for estimation is as follows: firstly, the mean delays are estimated through a 1-dimensional search by the cost function given in (7), then the value of each estimated mean delay is substituted in $\mathbf{R}(\tau_l, \sigma_l)$ (15), the corresponding standard deviation can then be estimated by through a 1-dimensional search over σ as follows:

$$\hat{\sigma}_l = \underset{\sigma}{\text{argmax}} \frac{1}{\|\mathbf{R}(\hat{\tau}_l, \sigma) \hat{\mathbf{U}}_n\|_F^2} \quad (17)$$

Simulation results

Simulations are carried out for an 12×12 MIMO system. Three clusters ($L = 3$) with associated mean delays $\tau_1 = 0.33T$, $\tau_2 = 0.51T$ and $\tau_3 = 0.72T$ are considered.

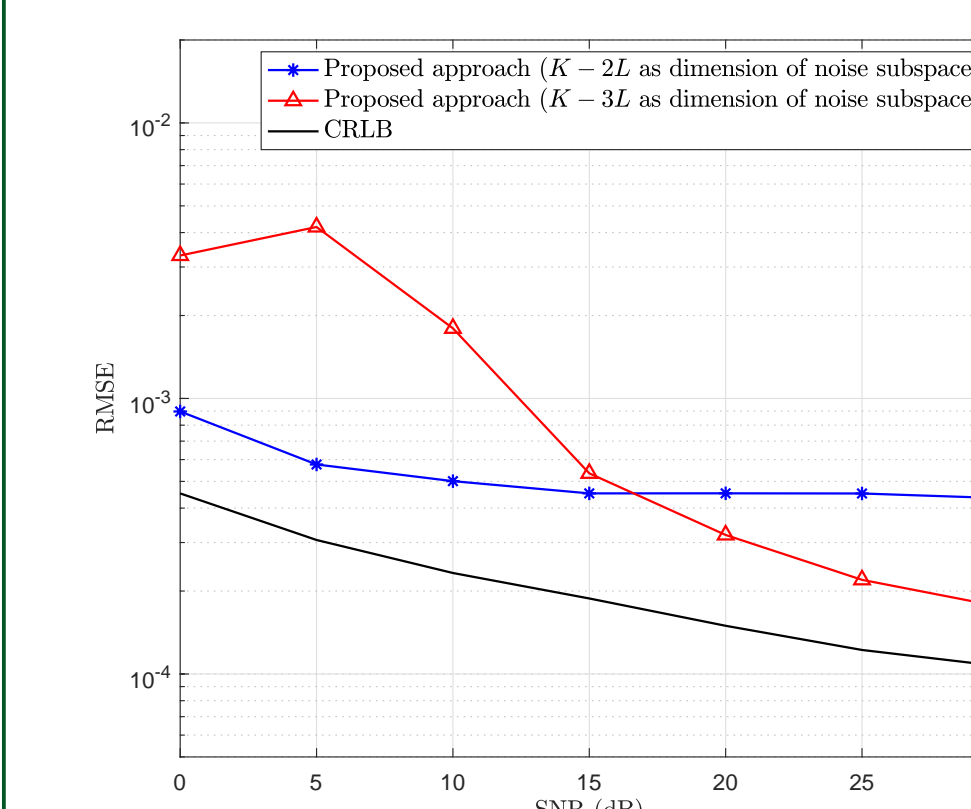


Figure 1: RMSE of standard deviation of delay spreading estimation vs SNR, $\sigma = 0.01T$ for all l .

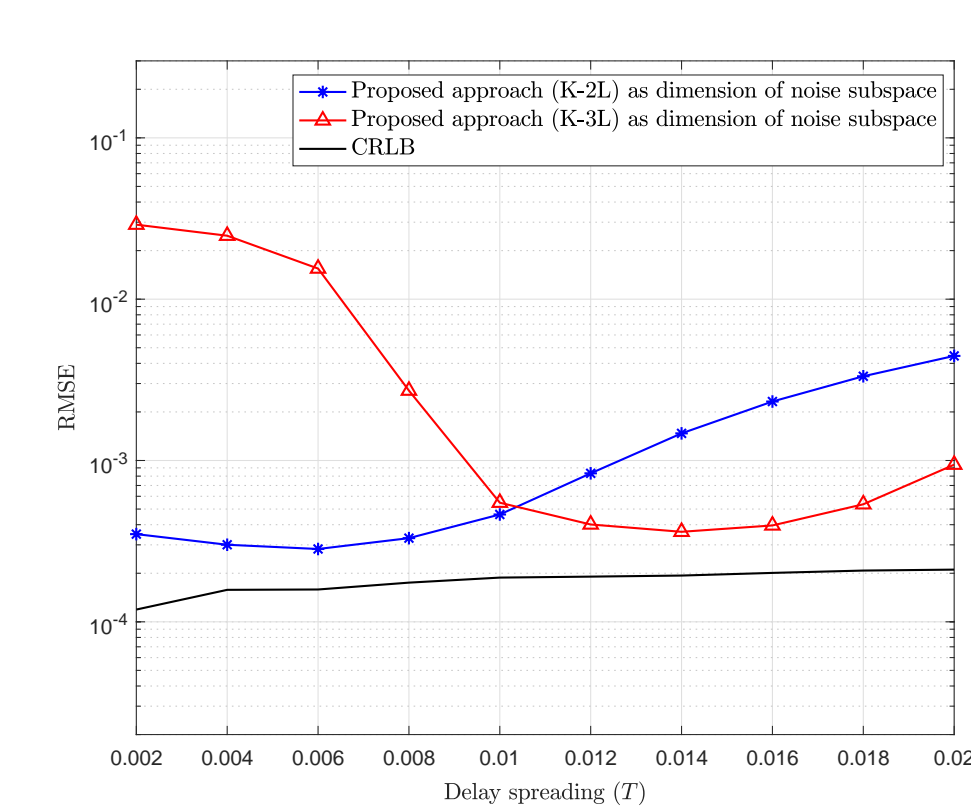


Figure 2: RMSE of standard deviation of delay spreading estimation vs standard deviation of delay spreading, SNR = 15 dB.

Conclusion

A scheme for estimating some statistical parameters of MIMO channel in scattering environments is presented. The proposed scheme has the ability to estimate two statistical channel parameters. Firstly, a deterministic model based approach is used to estimate the cluster mean delay, this estimated mean delay is then exploited to estimate the associated standard deviation of delay spreading through a stochastic model based approach that exploits the statistical distribution of the cluster multiray delays.