SUPER-RESOLUTION TECHNIQUE FOR ESTIMATING MIMO WLAN CHANNELS WITH APPLICATION TO 5 GHZ CHANNEL MEASUREMENTS

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ABSTRACT

In this paper we demonstrate how super-resolution techniques can be used to estimate WLAN channels. The method is based on the non-stationarity of the channel impulse reponse over time. We then use the method to study delay spread properties of measured WLAN channels at the 5 GHz band. We demonstrate how super-resolution techniques can be used to estimate the different delays of the reflections as well as the power variation. We validate the method based on an extensive set of channel measurements. We also estimate the statistical parameters of the fading process.

keywords: Channel measurement, 5 GHz, super-resolution, indoor radio propagation, wireless LAN, MIMO, IEEE 802.11.

1. INTRODUCTION

The development of WLAN systems for indoor use has shown rapid and accelerated growth in the last years. IEEE's latest PHY standards, 802.11a and 802.11g employ OFDM modulation in order to handle the highly frequency selective indoor channel. For each packet a preamble is transmitted, which allows the receiver to estimate the channel frequency response and its phase. Customary indoor wireless channel models [5], [3], [2], [1] use a sequence of impulses to model the reflections from objects and a "slow" ($f < 10$Hz) Doppler spectrum to model their movement. It has been assumed that this Doppler spectrum is the largest contributor to channel variability over time. As has been shown by the authors [7] in office environments, fluorescent lamps, typically used as the main source for light, coupled with magnetic ballast circuits, flicker, synchronized with the AC power line frequency, to create an interaction with the incident electromagnetic waves. This interaction, manifested by AM-like modulation of the received signal creates a large impact on the channel variability.

Previous measurement campaigns e.g., [10] used very large bandwidth to estimate the fine structure of the channel composed of delayed echos of the transmitted signal. The objective of this paper is to demonstrate how super-resolution techniques can be used to estimate the channels using relatively low sampling rate over a long period of time. We use the ESPRIT method, but other techniques such as MUSIC and MLE can be used as well.

2. DELAY SPREAD ESTIMATION

In this section we provide a simplified model for the data, and describe the delay spread model used. We then describe the method of estimation of the separate multipath reflections using super-resolution techniques.

The received baseband signal at antenna i, $x_i(t)$ is given by

$$x_i(t) = \sum_{j=1}^{p} h_{ij}(t)s_j(t) + n_i(t) \tag{1}$$

where h_{ij} is the channel response from transmit antenna j to receive antenna i, s_j is the PN sequence transmitted from antenna j and p is the number of transmit signals. We use almost orthogonal sequences for the various antennas. Note tha h_{ij} possibly includes the response of the transmit and receive filters which need to be removed from the data. This amounts to a simple calibration. The first phase of the analysis is a correlation of the received signal $x_i(t)$ with $s_j(t)$ to remove the effect of the other transmit antennas. We have used a PN sequence of period $2^{12} - 1$ (200 μs) and duration of 100 ms. After calibrating and correlating with the PN sequence we obtain time domain channel samples

$$\tilde{h}_{ij}(mT_s, lT_0) : m = 0, \ldots, M-1 \text{ and } l = 0, \ldots, L-1. \tag{2}$$

where T_s is the sampling time and T_0 is the time difference between consecutive channel estimates. In our case we have used $M = 64$ for the length of the channel response, and $L = 476$, which corresponds to about 100 ms measurement period. While both k and l are time indices, k describes consecutive channel response coefficients and $T_s = 0.05\mu s$ while l describes different channel instantiations separated by $T_0 = 200\mu s$. Switching to the frequency domain we obtain the frequency response of the channel given by

$$\hat{h}_{ij}(k,l) = \sum_{m=0}^{M-1} \tilde{h}_{ij}(mT_s, lT_0) e^{-2\pi j \frac{km}{M}} \tag{3}$$

We now turn to a parametric model of the channel response. We assume that the channel consists of a small number of reflections. The delays of each reflection are constant along a 100 ms period. Moreover we assume that the channel is non-stationary and the coefficient of each reflection varies along a period of 100 ms. Therefore the channel model is given by

$$\tilde{h}_{ij}(m,l) = \sum_{n=0}^{N-1} a_{ij}^{(n)}(l)\delta(mT_s - \tau_n) + \tilde{n}_{ij}(m,l) \tag{4}$$

where $\tilde{n}$ is the estimation noise. We assume the existence of N major reflections, with delays $\langle \tau_n : n = 1, \ldots, N \rangle$. $a_{ij}^{(n)}(l)$ are the attenuation and phase of the n'th reflection at the l'th block. We assume that these coefficients are randomly varying with time. Transforming into frequency domain we obtain that (4) now becomes

$$\hat{h}_{ij}(k,l) = \sum_{n=0}^{N-1} a_{ij}^{(n)}(l) e^{-2\pi j k \tau_n} + \hat{n}_{ij}(k,l) \tag{5}$$

Therefore the frequency response of each channel is a sum of complex exponentials modulating a random sequence. This model is well known in the signal processing literature. Stacking the channel estimates for various values of l will result in a low-rank matrix, with a rank equal to the number of reflections. We can now use any super-resolution technique to separate the reflections and obtain the time domain behaviour of the reflection coefficients. We have chosen to use ESPRIT [4] for this purpose, mainly due to its computational simplicity. Since the signal to noise ratio is very good we do not expect the choice of super-resolution method to be important. In a subsequent work we estimate the spatio-temporal structure using joint angle-delay estimation methods [11], [9]. From this point we fix the transmit and receive antennas and omit the i, j indices. Using matrix notation equation (5) becomes

$$\mathbf{H} = \mathbf{TA} + \mathbf{N} \tag{6}$$

where $\mathbf{H}$ is a $K \times L$ matrix given by

$$\mathbf{H} = \begin{bmatrix} \hat{h}(0,0) & \cdots & \hat{h}(0,L-1) \\ \vdots & & \vdots \\ \hat{h}(K-1,0) & \cdots & \hat{h}(K-1,L-1) \end{bmatrix} \tag{7}$$

$\mathbf{T}$ is a $K \times N$ Vandermonde matrix

$$\mathbf{T} = \begin{bmatrix} e^{-2\pi j 0 \tau_0} & \cdots & e^{-2\pi j 0 \tau_{N-1}} \\ \vdots & & \vdots \\ e^{-2\pi j (K-1) \tau_0} & \cdots & e^{-2\pi j (K-1) \tau_{N-1}} \end{bmatrix} \tag{8}$$

$\mathbf{A}$ is the $N \times L$ reflection coefficients matrix

$$\mathbf{A} = \begin{bmatrix} a^{(0)}(0) & \cdots & a^{(0)}(L-1) \\ \vdots & & \vdots \\ a^{(N-1)}(0) & \cdots & a^{(N-1)}(L-1) \end{bmatrix} \tag{9}$$

and $\mathbf{N}$ is a $K \times L$ noise matrix with covariance $\sigma^2 \mathbf{I}$. Using the Vandermonde structure of $\mathbf{T}$ we can now estimate the delays using ESPRIT. To ensure uniqueness of the solution we would require that $N < 0.5 \min(K, L)$.

3. MEASUREMENT SETUP

Nearly 1000 measurements of wireless channels at the 5GHz band were taken in a typical office space. Each channel measurement consisted of 480 channel matrices, sampled over a period of 100 ms, resulting in 480,000 MIMO WLAN channels. This enabled us to analyze the time variation of the channel matrix on the very short time scales of a single packet, as well as on various locations and longer time scales. Figure 1 depicts the building in which the measurements were taken. The locations of the transmitters are overlayed on the map and marked by numbers. Altogether we had 7 different locations varying from near line of sight (point 2) , short range (point 1) and long range (point 6).

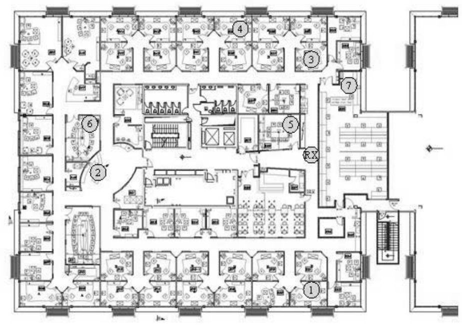

Figure 1: Floor plan of the second floor in the Metalink offices

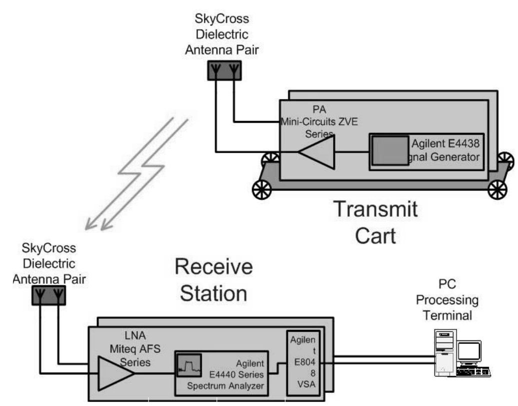

Figure 2: measurement setup

Figure 2 presents the 2 by 2 MIMO measurement setup for this experiment. The transmit setup consisted of two identical chains. Each chain was driven by an arbitrary signal generator transmitting a time shifted modulated PN sequence with a bandwidth of over 20MHz at a center frequency of 5.2 GHz. These signals were amplified by two power amplifiers feeding 2 omni-directional transmit antennas. The receive setup consisted again of two identical chains, with a pair of omni-directional receive antennas connected to two LNA's, used to amplify the signal, while maintaining a noise figure of less than 4dB. The signals were fed into a pair of spectrum analyzers used as down converters to an intermediate frequency (IF). The signals were then demodulated into base-band $(I\&Q)$, sampled and stored on a hardisk for offline processing. The offline processing included two PN sliding correlators. The result was the cross correlation between received signal and transmitted signal, which is the channel impulse response. The system was carefully calibrated using coaxial cables to make sure effects such as system noise figure and up and down converter frequency response were compensated for.

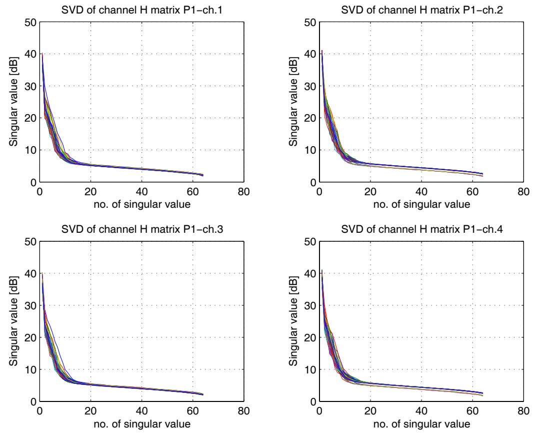

Figure 3: Singular value of the matrix $\mathbf{H}_{ij}$ (Generated using channels between Tx antenna $i = 1, 2$ and Rx antenna $j = 1, 2$ over 100ms) The various plots are for 50 different matrices over 3h period.

4. MEASUREMENT RESULTS

In this section we present the results of the channel analysis at various locations demonstrating the dominating effects on channel variability and fading. In all these experiments we have used K=64 and L=476 so we should be able to separate up to 31 reflections. The measurement bandwidth was 20 MHz which corresponds to temporal resolution of 50 ns per sample.

As we have seen in (6) the number of reflection is equivalent to the rank of the matrix $\mathbf{TA}$. We can estimate it from the eigenstructure using well known information theoretic criteria such as MDL or AIC, or simply threshold the eigenvalues at a sufficiently low value so the residual energy in the noise subspace is below the accuracy we would like to achieve. Figure 3 presents the singular values of 50 realizations of the matrix $\mathbf{H}$ sampled over a 3h period. Each realization used 500 channel frequency responses sampled over a period of 100ms. We can clearly see that the largest 8 singular values dominate all the others. Figure 4 depicts single realization of the channels between each transmit antenna and receive antenna. We can see that the 8 different reflections cannot be clearly identified without using super-resolution techniques. Using the estimated matrix $\mathbf{H}$ we have estimated the delays and the coefficients. Figure 5 presents the temporal amplitude variationsof the coefficients of each delay estimated for all channels between a transmit and receive antennas using 500 channel responses measured over a 100ms period. It is interesting to note that some of the reflections present 100 Hz periodicity, corresponding to the presence of fluorescent lamps in the building. As we have shown in [7] this leads to 100Hz periodicity (120Hz when the AC line frequency is 60 Hz) of the channel coefficients. Note also the slow variations due to Doppler spread (5-10 Hz) exist in some of the reflections.

Figures 6 and 7 presents the power of the reflections in dB as a function of the delays. We can clearly see the existence of exponentially decaying clusters corresponding to straight lines. This fits the well-known Saleh-Valenzuela channel model [5] thus providing another verification of the success of the super resolution technique to resolve the multipath.

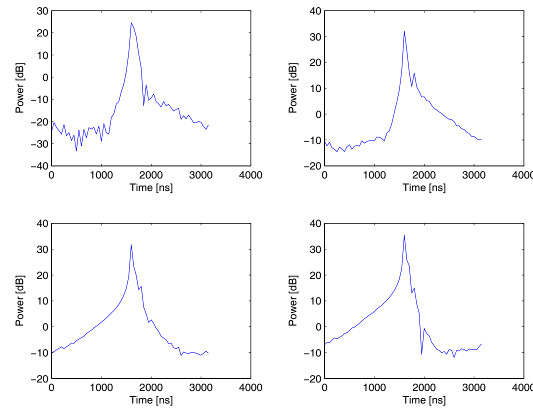

Figure 4: Single realization of impulse response of four channels between antennas

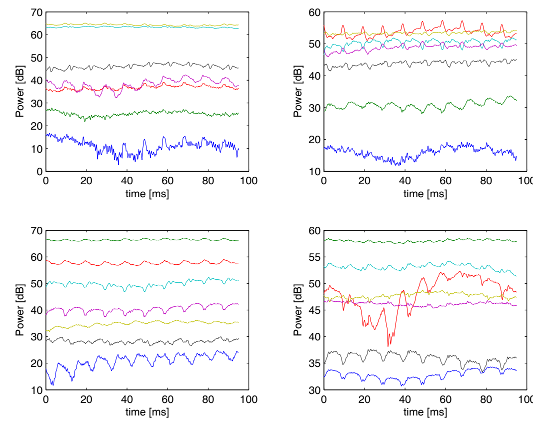

Figure 5: Temporal behavior of reflections power over 100ms period. Point no.7.

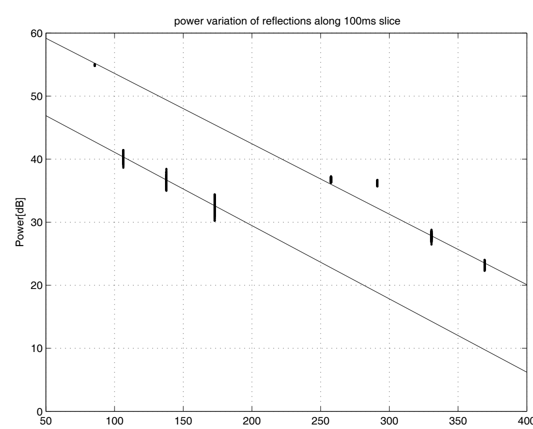

Figure 6: Power variation of reflections power over 100ms period. Point no.1.

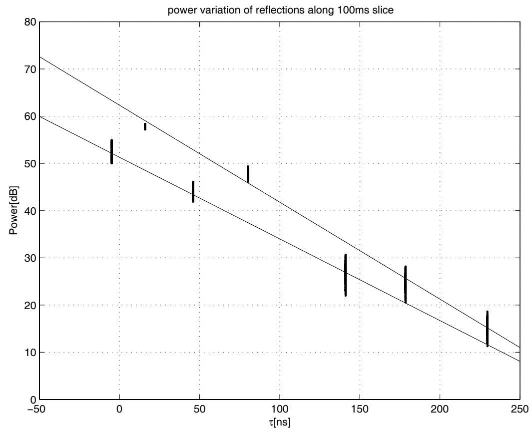

Figure 7: Power variation of reflections power over 100ms period. Point no.7.

5. CONCLUSIONS

In this paper we have shown that super-resolution time delay estimation can provide good estimates of channel coefficients even when the measurement bandwidth is significantly narrower than what has been used in previous measurement campaigns. This enables longer data records which are crucial in order to observe slowly varying channels. We demonstrated that the method separates stationary paths from time varying paths such as those caused by fluorescent lamps.

Natural extension of the techniques used to estimate the spatio-temporal structure of the channel can be developed based on joint angle delay estimation techniques such as MLE [6], [11] and multidimensional ESPRIT [8].

6. REFERENCES

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