

Higher frequency and higher power output units are at present under investigation.

J. M. LEISTEN
A. K. LEFEDJIEV*
L. HOBSON

21st February 1990

Electrical and Electronic Engineering Department
Brighton Polytechnic
Moulsecomb, Brighton BN2 4GJ, United Kingdom

* British Council Sponsored Researcher from Higher Institute of Electrical and Mechanical Engineering, Gabrovo, Bulgaria

References

- 1 OMORI, H., NAKAOKA, M., YAMASHITA, H., and MARUHASHI, T.: 'A novel type induction heating single-ended resonant inverter using new bipolar Darlington transistor'. Proc. 16th IEEE Power Electronics Specialists Conf., 1985, pp. 590-599
- 2 LEISTEN, J. M., and HOBSON, L.: 'An assessment of a class E induction cooking unit using a GTO'. Proc. 18th Power Conversion and Intelligent Motion Conference, 1989, pp. 329-353

AUTOREGRESSIVE MODELLING OF AN INDOOR RADIO CHANNEL

Indexing terms: Radiowave propagation, Modelling

An autoregressive model for the frequency domain characteristics of indoor radio channels is introduced. It is shown that a second order process is sufficient to represent the important statistical characteristics of the channel both in the frequency and the time domains. A comparison is made between the statistical characteristics of the empirical data and of the channel responses regenerated from the model.

Introduction: Wideband characterisation of the indoor radio channels has attracted tremendous attention in the recent years. Numerous time-domain measurements for various buildings^{1,2,4} and limited frequency domain measurements³ have been reported. The RMS delay spread of the time domain data and the 3 dB width of the frequency correlation function have been examined in these measurements. These parameters are inversely proportional,³ and are necessary for the calculation of the data rate limitation of the channel. The cumulative distribution function (CDF) of these parameters for various buildings are available in the literature.¹⁻⁴

The next challenge in this area was to develop a statistical model for computer simulation of the channel to evaluate the different communication techniques. The first model in the time-domain was introduced in Reference 2 and later on improved in Reference 4. The model in Reference 2 is shown to approximately reproduce the CDF of the RMS delay spread of the channel.

We show that the frequency domain measurements of the channel can be represented with an autoregressive model. Additionally, we show that such a model can reproduce close results for the CDFs of the 3 dB width of the frequency correlation function and the RMS delay spread of the channel. The advantage of this model over the time domain models is that it uses fewer parameters. It can therefore be simulated on the computer with considerable ease.

Autoregressive modelling: Fig. 1 shows a sample frequency response of the indoor radio channel measured with a network analyser.³ The measurement has been made at a set of evenly spaced frequencies

$$f_n = f_0 + nf_s \quad (1)$$

where $f_0 = 900$ MHz is the lowest frequency in the band of study and $f_s = 0.25$ MHz is the frequency sample spacing.

Assuming an autoregression model for the measured frequencies we have

$$H(f_n, x) = \sum_{i=1}^p a_i H(f_{n-i}, x) + V(f_n) \quad (2)$$

where $H(f_n, x)$ is the n th sample of the complex frequency domain measurement at location x , p is the order of the model, and $V(f_n)$ is a complex white noise sequence. The

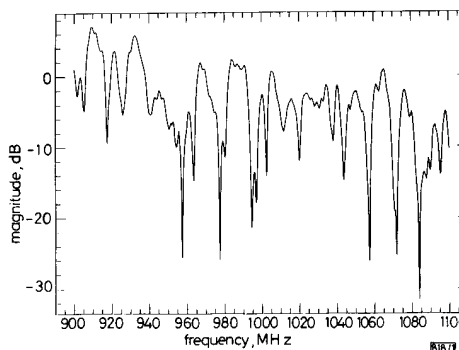


Fig. 1 Frequency response measurement

parameters of the model are the coefficients of the linear filter, a_i , that predicts the value of $H(f_n, x)$ based on previous values. Autoregressive modelling of the time domain data used for spectral estimation and the techniques for determination of the coefficients of the AR process are well known.⁵

In the AR modelling of the channel it is assumed that the observed samples of the process are the outputs of a linear filter with transfer function

$$G(z) = \frac{1}{1 - \sum_{i=1}^p a_i z^{-i}}$$

driven by a white noise signal $V(f_n)$. This filter is also represented by the p poles in the complex z -plane. Having solved for a_i , one sample of the random process $H(f, x)$ can be generated from eqn. 2 using a random sequence $V(f_n)$.

To determine the validity and the order of the model more than 300 frequency domain measurements were analysed at model orders up to 10. Typically, the magnitude of the largest pole was 0.95 or greater, the second pole was between 0.6 and 0.95, and the magnitude of the remaining $p - 2$ poles were around 0.5 making them insignificant. A scattered plot of the poles that resulted from a 5th order process for the 70 measurements taken in the IBM office at Worcester, MA, USA is shown in Fig. 2.

In the conventional parametric spectral estimation, a pole close to the unit circle represents significant power at the frequency related to the angle of the pole. The frequency is calculated as $f = \arg(z_i)/2\pi T_s$, where T_s is the sampling time.

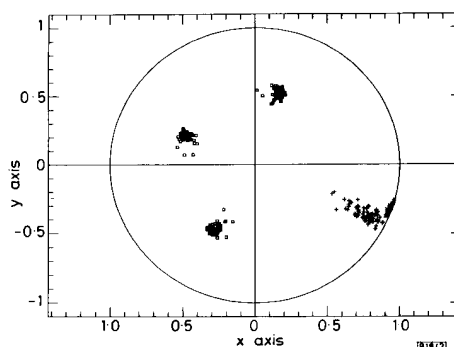


Fig. 2 Complex z -plane plot of poles for an AR model

In our application, the modelling is in the frequency domain and a pole close to the unit circle represents significant power at the time related to the angle of the pole. The time is calculated as

$$t = -\arg(z_i)/\omega_s$$

where $\omega_s = 2\pi f_s$ ($1/0.25 \text{ MHz} = 4000 \text{ ns}$). The arrival of the significant paths in all measurements are from 150 ns to 550 ns. This corresponds to the angular range of $-\pi/40$ to $-11\pi/40$. As shown in the scattered plots, at most two significant poles exist in this range. Based on these observations a two pole model is adequate to represent the indoor radio channel. Two significant poles can be interpreted as two significant clusters of multipath arrivals.

Comparison between empirical and model generated data: To demonstrate that a two pole model is adequate, all the measurements for the IBM experiment³ were examined. Using the first two poles of a 5th order model, the frequency domain characteristics of the channel were regenerated for all measurements. Fig. 3 shows the CDF of the 3 dB width of the frequency correlation function for both the original measurements and the regenerated data from the two pole model. Fig. 4 shows the CDF of the RMS delay spread for both the original measurements and the regenerated measurements. The frequency domain characteristics show a closer agreement with the original measurements, because the parameters of the model are determined from the second order statistics of the frequency domain autocorrelation function. This analysis was extended to the rest of the measured data and the results supported the above conclusions.

The interpretation of a pole as defining a cluster of paths and the distance from the unit circle as defining the power in the cluster provides a useful physical interpretation for the AR model introduced in this letter. The authors have developed a

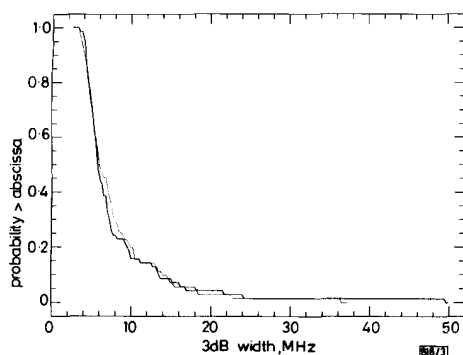


Fig. 3 CDF of 3 dB width

— IBM
..... AR model

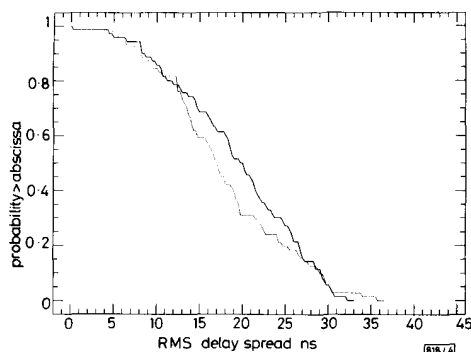


Fig. 4 CDF of RMS delay spread

— IBM
..... AR model

statistical model for the behaviour of the poles, which will be presented in subsequent publications.

Conclusions: A simple two-pole AR model was shown to be sufficient to model the frequency response of the indoor radio channel. The CDFs of the 3 dB width of the frequency correlation function and the RMS delay spread of the measured data and the model generated data were shown to be in close agreement.

Acknowledgments: This work was supported in part by the National Science Foundation under grant NCR-8703435 and a Raytheon Company fellowship.

S. J. HOWARD

20th February 1990

Raytheon Company
1001 Boston Post Road
Marlboro, MA 01752, USA

K. PAHLAVAN

Electrical Engineering Department
Worcester Polytechnic Institute
Worcester, MA 01609, USA

References

- PAHLAVAN, K., GANESH, R., and HOTALING, T.: 'Multipath propagation measurements on manufacturing floors at 910 MHz', *Electron. Lett.*, 1989, **25**, (3), pp. 225-227
- SALEH, A. M., and VALENZUELA, R. A.: 'A statistical model for indoor multipath propagation', *IEEE J. Sel. Areas Commun.*, 1987, **SAC-5**, pp. 128-137
- PAHLAVAN, K., and HOWARD, S. J.: 'Frequency domain measurements of the indoor radio channels', *Electron. Lett.*, 1989, **25**, pp. 1645-1647
- GANESH, R., and PAHLAVAN, K.: 'On the modeling of fading multipath indoor radio channels', *Proc. IEEE GLOBECOM'89*, Dallas, TX, 30 Nov. 1989, pp. 1346-1350
- MARPLE, S. L.: 'Digital spectral analysis' (Prentice-Hall, Englewood Cliffs, 1987)

EFFECT OF INITIAL CONDITIONS ON LIMIT CYCLE PERFORMANCE OF SECOND ORDER SAMPLED DATA SIGMA DELTA MODULATOR

Indexing terms: Control theory, Modulation, Nonlinear systems

Sensitivity studies on the effects of initial conditions on the limit cycle of a second order sampled data sigma delta modulator are presented. It was found that a sequence of modes exists whose time ratios conform to a simple hyperbolic pattern.

Introduction: In many nonlinear sampled data systems a variety of possible limit cycle modes may exist.¹ In certain nonlinear sampled data systems for which there are many possible limit cycle modes it is common that only a limited number may be practically encountered. The full set can only be produced under special conditions. A practical example of a nonlinear sampled data system exhibiting the above properties which is of international interest in telecommunications and signal processing applications is the second order sigma delta modulator described by Candy² and Agrawal and Shenoi,³ the discrete model of which is given in Fig. 1 (both the Candy and the Agrawal and Shenoi papers nominate values of 0.5 and 1 for the parameters A and B, respectively). A sampled describing function (SDF) analysis of this and similar systems has been undertaken⁴ revealing the possibility of (1, 1), (2, 2) and (3, 3) modes, where a (k, k) mode refers to a symmetric limit cycle oscillation containing k sampling inter-