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STATISTICAL CHARACTERISATION OF DYNAMIC PROPAGATION ENVIRONMENTS FOR MOBILE WIRELESS COMMUNICATION SYSTEMS

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Abstract – We present results of experiments for characterising complex (i.e., multiple-scattering and time-varying) environments for propagation of microwaves. Parameters of the distortion of the received signals are analyzed using statistical and stochastic methods.

Keywords: wireless communications, complex propagation environments, stochastic processes, linear time-varying systems.

1. INTRODUCTION

Classical point-to-point wireless communication systems suffer from "cold spots" of relatively poor reception of the signal, an effect known as *fading*. Physically, multipath fading occurs as a result of atmospheric variations or because of destructive superposition of reflections of an impinging radio wave from surfaces and objects, producing scattered and diffracted waves that recombine locally with large relative phase differences. The problem is a general one for point-to-point narrowband systems. On the other hand, modern communication systems based on distributed multiple-input-multiple-output (MIMO) communication systems, equipped with so-called "smart antennas" with associated signal processing capabilities, are exploiting fading as an opportunity for *increasing* the quality of the communication link and/or the capacity of the communication channel in a static environment. Resolving fade-ins and fade-outs at the receiver end allows for spatially multiplexed data streams, enabling diversity, in space, time, frequency and polarization.

Although MIMO is a primary candidate for the realization of forthcoming 4th generation (4G) wireless communication systems (WiMAX), the variable Doppler shifts occurring in high-speed motion at the transmitter and/or receiver in terrestrial non-line-of-sight (NLoS) links remains a major obstacle in achieving high data rates needed for broadband real-time data streaming, e.g., for television and internet video on-the-move, in high-speed trains or cars. For example, a 4x4-MIMO system based on COFDM (coded orthogonal frequency division multiplexing, as used in e.g., the DVB-T standard) achieves 1 Gbit/s when stationary, while the channel capacity drops by a factor of ten when the transmitter or receiver moves with a relative velocity of as low as 8 km/h [1], with current channel capacity limited to around 20 Mbps. Clearly, the time variation of the multipath components, in amplitude, phase and direction of propagation (and, with it, the electromagnetic (EM) wave structure (spatial map) of each of the three Cartesian components of the vector electric field across an extended volume) has a significant effect on the overall level of signal distortion in dynamic environments and requires detailed investigation.

2. EXPERIMENTAL STUDY

2.1. Mode-Tuned Operation

2.1.1 Paddle Transitions with CW Excitation

To investigate experimentally the effects of multipath fading on signal distortion in dynamic EM environments in a controlled and repeatable manner, we use an EM mode-tuned reverberation chamber (MTRC). A MTRC is in essence an overmoded resonant cavity, with large dimensions compared to the wavelength and producing an echoic multi-path environment that strongly varies in time by the action of a step-wise rotated large reflective paddle wheel inside. The result is a discrete stochastic process (time series) for the local internal field. An account of the central limit theorem, it can be shown theoretically that the statistics of the field magnitude and power or energy density inside an MTRC at sufficiently high frequencies obey chi- and chi-square probability density functions (pdfs), respectively, corresponding to and ideally statistically isotropic and homogeneous EM random field. By rotating the paddle wheel at a sufficiently low constant speed, the EM boundary configuration changes in a quasi-static manner.

Conceptually, the configuration can be characterized as a linear time-varying (nonstationary) system, specifying a three-dimensional EM boundary-value problem in space-time with time-varying parameter values. Because the environment is highly resonant and strongly dispersive, one must distinguishes between nonstationary effects due to mechanical effects (rotational speed, stopping time) – yielding deterministically or randomly time-varying parameters of the associated governing differential equations for the interior field – and purely EM nonstationary effects (cavity relaxation (ringing) time) that are a result of the time-dependent modulated source term in these equations.

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An important metric in signal transmission is the modulation index, *m*. In amplitude (AM) and frequency (FM) modulation, this quantity is a measure for the modulation depth and, with it, its resilience to noise and fading. In a dynamic multipath environment, this quantity becomes a random variable and is defined by [2]

$$M(t) = \frac{P'(t)}{P(t)} = 2\frac{A'(t)}{A(t)} \qquad (1)$$

where $P(t)$ and $A(t)$ are the instantaneous field intensity and amplitude, respectively, at time t. Practical assessment inevitably involves sampling of waveforms with sampling interval Δt, resulting in a modulation coefficient $M(t,\Delta t)$ which can be show to approach $M(t)$ in the limit $\Delta t \to 0$ (continuous trace).

Figure 1 shows the evolution of the ensemble average value of $M(t,\Delta t)$ taken over a realized ensemble (sample set) of 100 independent stir states (i.e., sets of multipath components) in the course of continuous motion (stirring) of one of the boundaries of the cavity. It can be seen that the motion introduces a relatively *regular* modulation of the signal. Theoretical models can be devised to quantitatively predict these experimental results for $M(t,\Delta t)$ [3], as well as the evolution of the probability density function of the instantaneous field using a generalized diffusion model based on a nonstationary random walk [4].

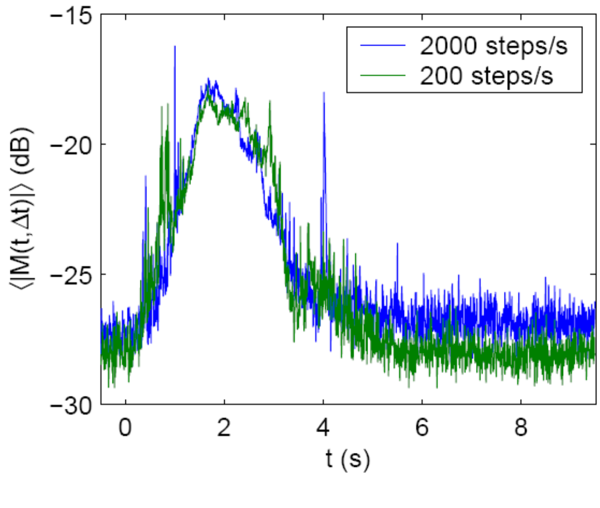


Fig. 1: Ensemble average value of sample modulation index as a function of time during transitions of a moving boundary inside a mode-stirred reverberation chamber.

2.1.2 Pulsed Excitation in Mechanical Steady-State

Modulated signals can be significantly distorted as a result of multipath reflections. Figure 2 shows the measured response to an AM square-wave input signal measured. Because of the changing boundary conditions (1000 paddle wheel steps), each pulse response is different but statistically equivalent, due to the constant mode density. This results in an ensemble of pulse response functions. In this case, the dynamics of the EM environments are due to the transient effects caused by the cavity relaxation time, rather than any sample-continuous change in boundary conditions as in the previous case. It can be seen that the standard deviation of the received power or intensity is of the same order of magnitude as the average value, for any delay $m\Delta t$ from the start of the signal, which is important for estimating uncertainties of the signal distortion for different delays.

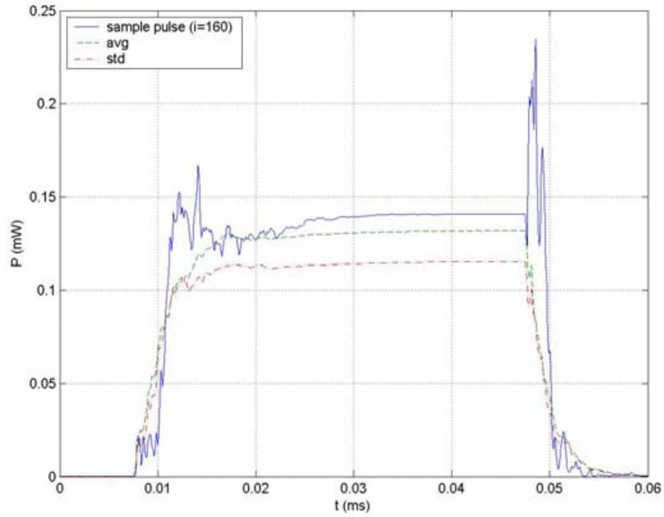


Fig. 2: Typical received distorted signal (blue line) for rectangular input pulse, together with ensemble average (green dashed line) and ensemble standard deviation (red dash-dotted line) for a population of 1000 statistically equivalent multipath environments.

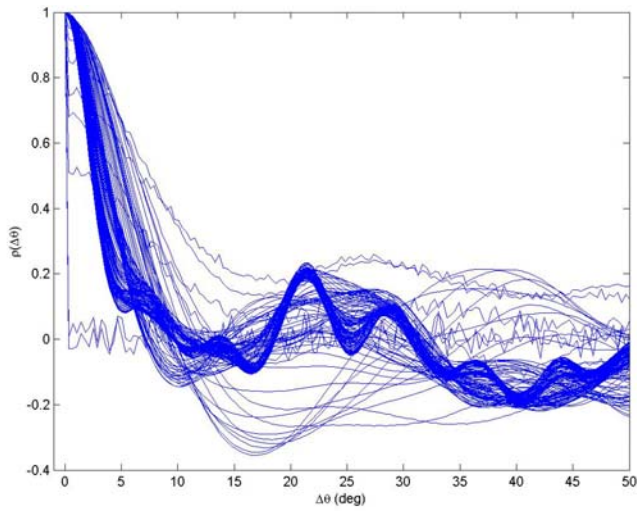


Fig. 3: Evolution of the autocorrelation function of a received pulsed signal inside a reverberation chamber as a function of the angular increment $\Delta\theta$ of a rotating paddle wheel. Each curve represents a correlation function for a fixed elapsed time $m\Delta t$ after the start of the pulse t_0 (m=0, 1, …, 300; Δt = 5 ns), taken at different positions of the paddle wheel.

A more difficult problem constitutes the evolution of the correlation length [5]. This parameter is of crucial importance in estimating the antenna spacing in MIMO systems. To this end, we measured electric power density for a pulse-modulated input signal train and investigated the temporal correlation function across this pulse train. The results are given in Figure 3 for the autocorrelation function $\rho(\Delta\theta)$ (in terms of the angular increment of a paddle wheel as the moving boundary inside the cavity), showing that different epochs during the pulse duration are differently correlated. This has important consequences for signal synchronization and, hence, for the maximum channel capacity inside a dynamic EM environment.

2.2. Mode-Stirred Operation

Additional measurements were performed for the chamber operating in *mode-stirred operation*, i.e., for continuous rotation of the paddle wheel. Strictly, since the paddle wheel is driven by a stepping motor, this is still a discretised mode of rotation. However, in mode-stirred operation, there is no longer an additional dwell time between steps. Also, because of mechanical inertia, the resulting mechanical motion is effectively continuous.

Specifically, a pulse train with pulse repetition frequency of 10 kHz (pulse period 100 μs) was generated by a pulse generator (150 ps rise time) modulating a time-harmonic RF signal fed to a biconical transmitting antenna. The signal received by another, identical antenna – while the paddle wheel rotates – was processed by a real-time spectrum analyzer, which sampled the received pulse responses with an acquisition bandwidth of 40 MHz or 110 MHz (Δt = 20 ns or 6.67 ns as sampling interval). The lower sampling rate permits to collect data for a full rotation of the stirrer at its maximum speed of revolution, viz., V=10,000 motor steps per second, resulting in a rotation period of 4 s and yielding one pulse per motor step (i.e., 40,000 pulse periods), each consisting of 5,000 time samples.

By measuring the pulse response at different rotation speeds and accelerations, the extent and effect of nonstationarity on the pulse response and signal distortion can be measured and quantified. Figure 4 shows one pulse response period with acquisition bandwidth of 40 MHz.

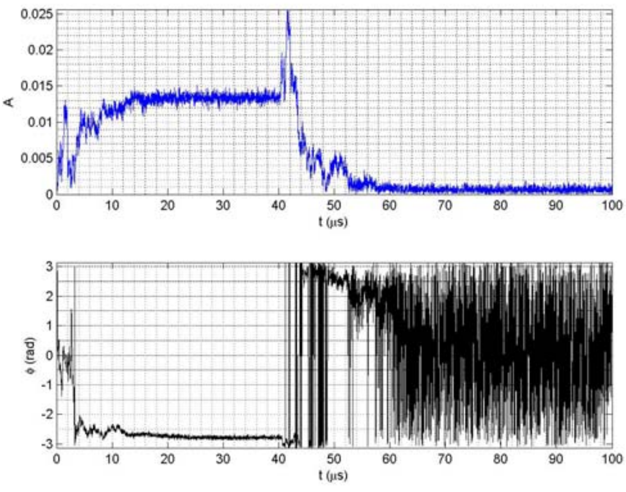
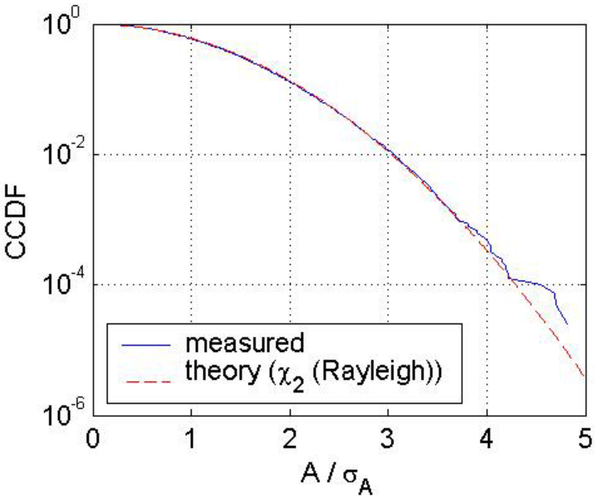
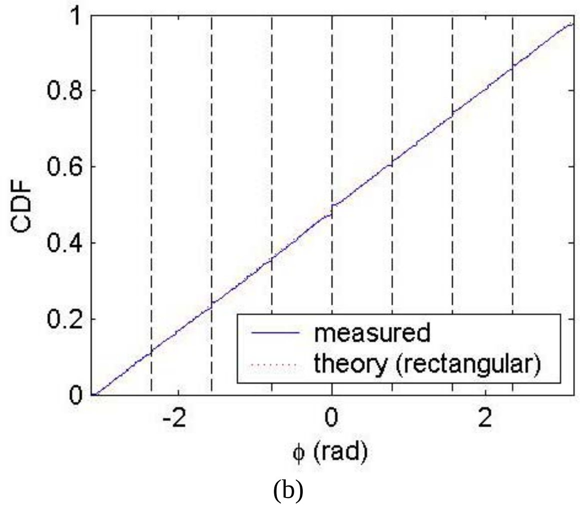


Fig. 4: Single period of pulse response for mode-stirred field.

Prior to analysing the statistics of the received field, a "calibration of statistics" for the measurement system was performed, as follows. Figure 5 shows the complementary cumulative distribution function (ccdf) of the amplitude and cdf of the phase for the pulse responses in the "off"-state, i.e., for pure noise measured at a delay t-nt_0=70μs, when the pulse amplitude has reached steady-state (completed decay). The measured ccdf closely follows the theoretical Rayleigh (χ_2) ccdf for idealized quasi-stationary random fields, almost to within the statistical resolution limit, 1/40,000 = 2×10^{-5}. The phase is nearly uniform (having a theoretical rectangular distribution). Note, however, that deviations occur at multiples of $\pi/4$, particularly near 0 and $\pm\pi$.



(a)



(b)

Fig. 5: Measured vs. theoretical probability distributions for mode-stirred operation in "off"-state, at t-nt_0=70μs (n=0,…,N-1) for N=40,000 pulse responses across one full paddle wheel rotation; (a) complementary cdf of field magnitude A; (b) cdf of phase ϕ.

Next, the analysis is repeated for the "on"-state, viz., at delay t-nt_0=30μs, which is again sufficiently far removed from both leading and trailing edges to warrant steady-state if the paddle wheel were rotating arbitrarily slowly, with associated χ_2 amplitude statistics [5]. First, by way of verification, a close-up view of the resulting 40,000-point stir sequence (30μs-slice), shown in Fig. 6, confirms that this sequence forms a quasi-continuous trace, with the small ripple attributable to residual time jitter of the excitation pulse train. Figure 7 shows the corresponding ccdf and cdf. The amplitude characteristics appear to be affected.

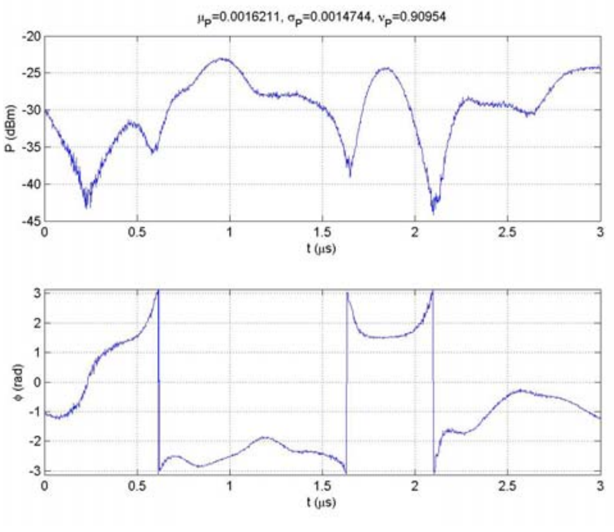
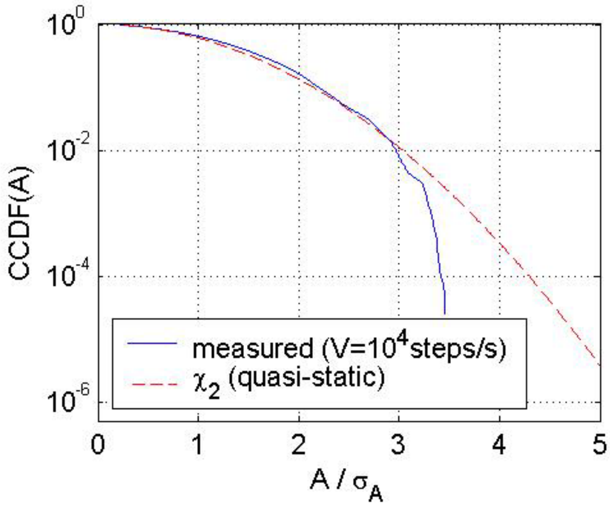


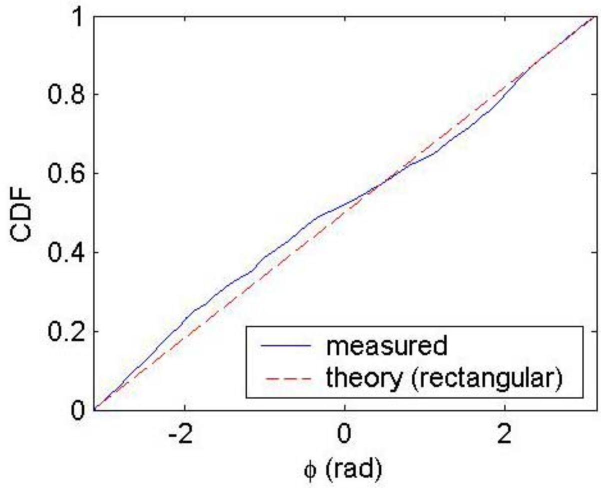
Fig. 6: Close-up of part of measured stir sweep of received power and phase ϕ (use magnification of electronic version to inspect magnitude of ripples).

3. CONCLUSIONS

We demonstrated a statistical framework for analyzing time-varying electromagnetic systems relevant to mobile wireless communication systems. Time variations as a result of changes in boundary conditions, as well as transients in pulsed signals caused by cavity relaxation, were analyzed.



(a)



(b)

Fig. 7: Measured vs. theoretical probability distributions for mode-stirred operation in "on"-state, at t=nt_0+30μs (n=0,…,N-1) for N=40,000 pulse responses across one full paddle wheel rotation; (a) complementary cdf of field magnitude A; (b) cdf of phase ϕ.

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REFERENCES

[1] K. K. Young and R. Prasad, *4G Roadmap and Emerging Communication Technologies*, Artech House 2006.

[2] L. R. Arnaut, Time-domain measurement and analysis of mechanical step transitions in mode-tuned reverberation, *NPL Report*, DEM-EM-012 (Oct. 2006), pp. 1-164.

[3] L. R. Arnaut, On the maximum rate of fluctuation in mode-stirred reverberation, *IEEE Trans. Electromagn. Compat.*, vol. 47, no. 4 (Nov. 2005), pp. 781-804.

[4] L. R. Arnaut, Nonstationary random acoustic and electromagnetic fields as wave diffusion processes, *J. Phys. A: Math. Theor.*, vol. 40, no. 27 (Jul. 2007), pp. 7745-7788.

[5] L. R. Arnaut and D. A. Knight, Observations of coherent precursors in pulsed mode-stirred reverberation fields, *Phys. Rev. Lett.*, vol. 98, no. 5 (Feb. 2007), 053903.