Characterization of an Empirically-Derived Database of Time-Varying Microwave Channel Responses

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Abstract

This paper reports on the gathering, processing, and categorization of empirically derived time-varying channel responses. The passband data and data collection information is provided courtesy of Applied Signal Technology (Sunnyvale, CA). It is the intent of this paper to provide the signal processing community with a database of time-varying fractionally-spaced channel responses and received sequences based on empirical measurements which can be used to test and refine existing time-varying channel models and also propose new ones.

1. Introduction

A common assumption in analysis of blind equalization and identification techniques is that of a linear, *time-invariant* channel model. Many existing and emerging applications, however, challenge this time-invariant assumption. While many time-varying models are proposed in the literature, some are suspect in a practical setting and few are data-based.

In the Spring of 1996, Applied Signal Technology (Sunnyvale, CA) collected data to empirically assess the impact of a wideband mobile communication environment on digital communications [1]. A vehicle with a receiver and an antenna collected digital microwave transmissions from stationary sources for approximately six weeks in Northern California. We at Cornell University and our colleagues were given access to Applied Signal Technology's raw field data with the promise to "prepare" it for use by the general signal processing community.

Our intent with this data is to provide the community with an empirically-derived database which can be used to test and refine existing time-varying models and possibly propose others in an effort to meet the needs of today's demanding applications. To this end we have written demodulation software (MATLAB and C) which provides, among other things, (approximately) length-130,000 $T/2$-spaced, complex-baseband received sequences, and successive channel estimates over this observation window. Moreover, due to Applied Signal Technology's substantial effort in the field, the database is quite large. Hence we also attempt a classification of the data into three (possibly overlapping) categories: stationary or slowly time-varying, non-stationary, and unprocessable using standard blind demodulation techniques such as CMA [5].

The sequel is organized as follows. §2 describes the data collection procedure and field experiments. §3 describes our subsequent data processing and demodulation procedure. §4 provides some demodulation results and a classification of the experiments. §5 lists some observations based on the data and §6 contains concluding remarks and a summary of internet addresses for data access.

2. Data Collection

In April and May of 1996, Applied Signal Technology performed experiments in the Northern California area near Red Bluff to determine demodulation requirements for on-the-move (OTM) high data rate digital communications. A fixed source with 40 MHz bandwidth at radio frequencies of 4.45 and 7 GHz transmitted QPSK data at 50 Mbps (25 Mbaud). The source, although stationary during a single experiment, was moved several times during the six week period. The receiver was battery powered and mounted in

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a four-wheel-drive vehicle with a horn antenna above the roof. OTM data was collected for mobile velocities from 5 to 50 mph at distances between 1 and 40 miles. We calculate the impact of the Doppler shift on the signalling rate to be less than 2 Hz or approximately 1% of the observed baud frequency timing error. The physical characteristics of the experiments varied greatly, from having an unobstructed line of sight to being shadowed by a hill or being blocked by a passing truck.

The data was collected using Applied Signal Technology's Model 195 Snapshot Recorder/Analyzer with 64 MBytes of memory and a sample rate of 200 MHz, which at 25 Msymbol/sec corresponds to 8 samples per symbol.[3] A sample power spectrum of the 70 MHZ IF receiver output is shown in Figure 1. Typically, OTM data was collected in 0.5 MByte successive snapshots at 0.1-0.5 second timer-controlled intervals and stored on disk for subsequent processing. It was predominantly these OTM multi-snapshots of data collection, separated by off-the-air intervals, that we post-processed in §3. There exist 114 data files, most of which contain 8-40 0.5 MByte successive snapshots, for a total of 1.2 GBytes of data representing varied physical experiments.

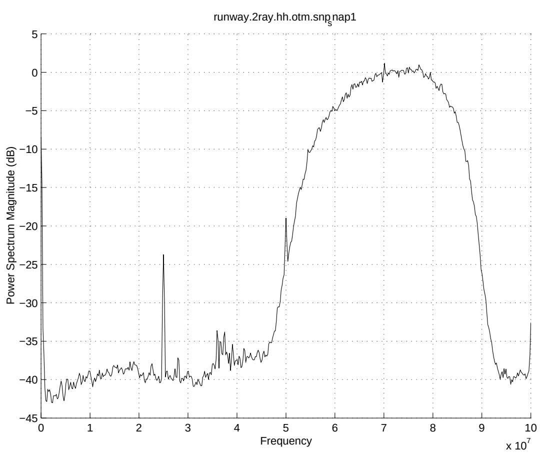

Figure 1. Typical passband spectrum

3. Data Processing

The data processing is all MATLAB software based (with C-MEX files) and consists of two primary functions; a QPSK demodulator and a channel estimator.

The QPSK demodulation software is comprised of four blocks (see Figure 2):

1. a data reader and converter: getdata(·)
2. a complex baseband/resampler: c_base_resamp(·)
3. a looping blind equalizer: cmaloop(·)
4. a looping DD carrier-tracker/equalizer: ctrac_eql(·).

[3]Our demodulation procedure in §3 resamples the data to two samples per symbol, as well as accounting for baud frequency errors which we observed to be on the order of 100-200 Hz.

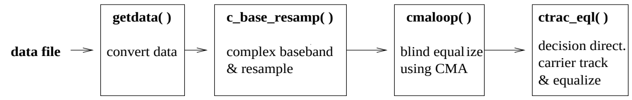

Figure 2. Demodulation software flow

Block 1 simply reads in the packed binary data and converts it to an array of floating point values. Block 2 nominally complex basebands the signal and uses band-edge timing recovery (BETR) [4] and (interpolated-coefficient) polyphase resampling to provide baud-synchronous sampling at twice the symbol clock rate. The BETR technique is aided by an interpolated-FFT technique which estimates the mean deviation in received symbol rate from the specified 8 samples per symbol. Block 3 takes the T/2-sampled output of Block 2 and blind equalizes using the Constant Modulus Algorithm (CMA) [5] over the first half of a single snapshot. The module makes multiple (3 was the number used in the processing reported here) forward and backward passes, maintaining baud continuity, to reduce the error rate sufficiently for transfer to a decision-directed (DD) equalization mode. Block 4 uses the equalizer estimate from Block 3 and simultaneously does equalization and decision-directed carrier tracking. As in Block 3, the software makes multiple (2 was used in the processing) forward/backward phase-continuous passes through the data. The primary outputs are the numerically controlled oscillator (NCO) values representing the residual carrier, and soft and hard symbol decisions. The NCO is applied to the nominally complex basebanded data (frequency translated down by 70 MHz) to remove the residual carrier and hence provide the "desired output" sequence for the channel estimator.

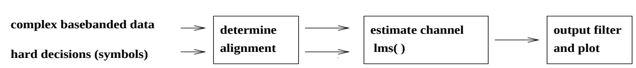

Figure 3. Channel estimation software flow

The channel estimator uses LMS [3] (RLS was also tried with similar results) to provide estimates of the complex baseband T/2-spaced channel. (See Figure 3.) The hard decisions (estimated symbols) with interleaved zeros comprise the "input" sequence and the complex basebanded data comprises the "desired output" sequence. (See [2] for further discussion of this channel estimation procedure.) The two sequences are complex correlated to determine an appropriate system delay and then the LMS algorithm is run over successive sections (most of the experiments use 4 sections, each which are 1/4 of the .5 megasample snapshot) of the data snapshot.

Both the equalizer and channel filters were 100 coefficients, which appeared to be adequate for almost all files. A step size of .001 was used for both CMA and LMS. Some experiments were conducted with reducing the step size for successive loops of the blind equalizer but there was no significant change in the quality of the demodulation.

All of the software was written to run under MATLAB 4.2. The algorithms used in the demodulation are all designed for arbitrary QAM signals. However, for expediency and efficiency some of the functions and scripts have been tailored to QPSK. The equalizer, carrier tracker and LMS routines have been re-written in C and compiled as MATLAB executables known as MEX functions. These MEX functions run 10 to 50 times faster than the corresponding MATLAB functions and allowed processing the entire 1.2 Gigabyte database in a reasonable amount of time.

4. Data Categorization

With such a large amount of field data gathered, a useful task was to delineate the severity of the signalling environments for the various experiments and group the data files. To this end, using the demodulation software described in §3, we selected OTM files and categorized a subset of them. Presently, selected data (in the form of passband data, channel estimates and $T/2$-spaced received sequences) and the demodulation code discussed in §3 are available at Cornell University BERG's web page at

http://backhoe.ee.cornell.edu/BERG

though the intent is to move this information to the signal processing database maintained at Rice University [6]

http://spib.rice.edu/spib.html

We looked for short-term (within the time typical for convergence of the blind equalization algorithm) time variations. Our method for categorization therefore considered four consecutive channel estimates over a snapshot (i.e., one channel estimate every $130{,}000/4$ $T/2$-spaced observations) and determined (with the help of the measures returned from the software) if these channel estimates suggested (i) legitimate time variations, (ii) nearly stationary environments, or (iii) poor demodulation. Tables 1, 2, and 3 show our classification of files according to these categories, respectively. Because each file contains multiple snapshots (8-40 contiguous .5 Mbyte data blocks) we classified the entire file as having significant time variations (i.e., in (i)) if any of the single snapshots suggested this behavior. Indeed, it was often the case for those files which suggested legitimate time variations that only a handful of snapshots (out of the 8-40 possible) motivated the file's inclusion in this category. In such cases, we marked which snapshots were of interest.

Our intent was that this categorization aid in minimizing the initial work that would otherwise be necessary by other researchers in using this data. We admit, however, that our processing was not exhaustive and more experiments could be performed to optimize the demodulation of files for which the equalizer failed to "open the eye".

5. Observations

Our main observations based on the data include:

1. Many experiments suggested insignificant time variations or nearly stationary signalling environments after baud synchronous resampling. See Table 2.

2. The "significant" portion of the estimated channel impulse responses was typically within a 500 nsec window.

3. It was not always the first channel peak which was the largest, indicating non-minimum phase propagation channels [4]. For example, see Figure 4 which shows snapshot 10 of file *hillshadow.otm.4GHz*.

4. The majority of the files in Table 3 were likely low SNR files due to the receiver being over 30 miles from the transmitter.

5. In some cases a second ray was observed to "bob" up and down. For example, see Figure 5 which demonstrates longer-term time variations by showing one channel estimate each from snapshots 7-10 of file *hillshadow.otm.4GHz*.

6. A lack of baud sychronization can be mistaken for a channel time variation, where, for instance, the estimated channel coefficients can be seen to "roll" in time. For example, see Figure 6 which is a "close-up" (shows channel taps 40-60) of snapshot 15 of file *oxbox.otm*. However, in most cases the baud-timing estimation was accurate enough so that no time variations attributable to timing errors were evident.

7. It was observed that the attenuation of the channel varied significantly over time for some of the files. For example, see Figure 7 of snapshot 13 of file *bowman.4GHz.VV.otm*.

8. In some instances, the software discussed in §3 was able to reliably demodulate data files for which the techniques of [1] failed.

[4] One implication here concerns Decision Feedback Equalizers (DFEs). The relatively long pre-cursor evident in these channel estimates requires a long forward equalizer within the DFE structure. Performance benefits of the DFE over a feedforward fractionally-spaced equalizer alone are therefore questionable.

9. The field data was created using a (hardware) degree 15 linear recursive bit generator, which unfortunately began malfunctioning, producing bit slips in much of the OTM data files. Thus, though the underlying structure was used for error estimates, it could not reliably be used for error correction.

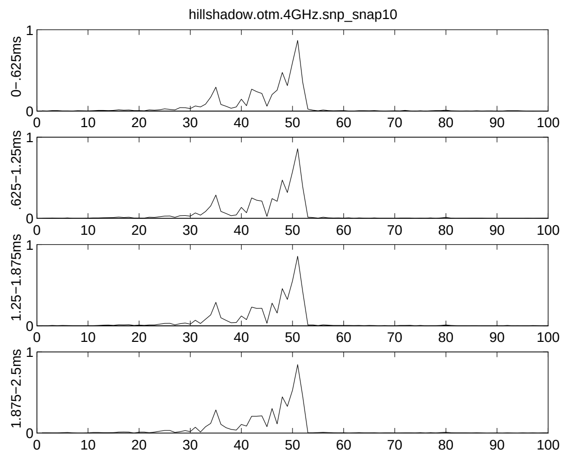

Figure 4. Consecutive channel estimates from snapshot 10 of *hillshadow.otm.4GHz* **showing that the dominant ray is not always the first.**

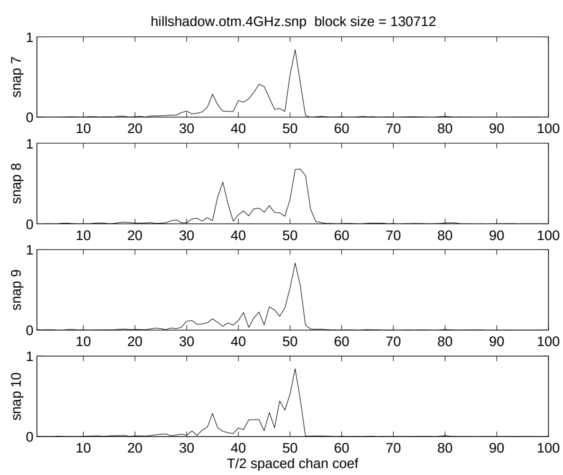

Figure 5. Channel estimates from snapshots 7-10 of *hillshadow.otm.4GHz* **showing time variations spaced .2 seconds apart.**

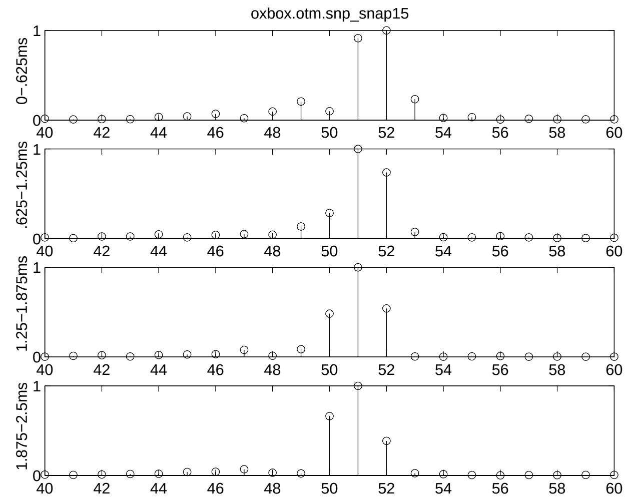

Figure 6. Consecutive channel estimates from snapshot 15 of *oxbox.otm* **showing the effect of a baud frequency timing error.**

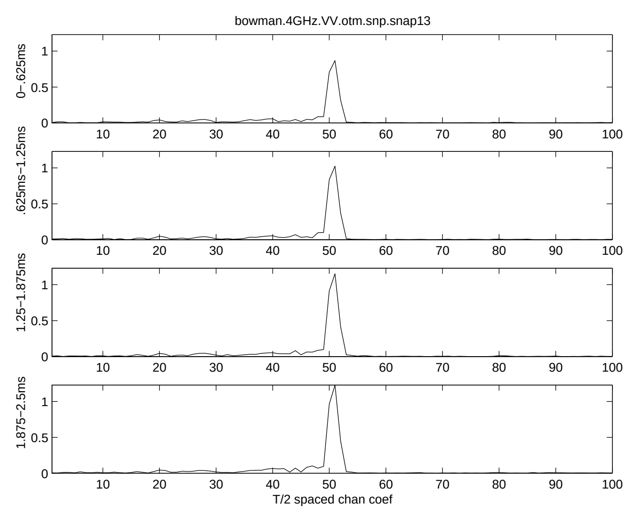

Figure 7. Consecutive Channel estimates from *bowman.4GHz.VV.otm* **showing time varying attenuation.**

6. Conclusion

This paper has summarized the collaborative efforts of Applied Signal Technology and the Blind Equaliza-

Table 1. Significant Time Variations

File	Snapshots of interest
beegum.otm.multi	3
beegum.otm1.multi	2
bowman.4GHz.VV.otm	13,15
bowman.4GHz.VV.otm1	8-10
bowman.7GHz.VV.otm1	3, 20
hillshadow.otm.4GHz	1-4,6-20 low cluster var.
hillshadow.otm.4GHz.1	2,3,5,6,8,10-19
hillshadow.otm.7GHz	5-7,10-20
hillshadow.otm.7GHz.1	all
oxbox.otm	4,12-15,18-20,22,26,28-37
oxbox.otm1	11,12,15-17,25-27,30-32,36
preoxbow.otm2	5,16,18,21,22,30,39

Table 2. Stationary or "Mild" Time Variations

File	Comments
beegum.four.otm	1-9,14,18-29,34,38-40
bowman.store.7GHz	cluster variance $\approx -25dB$
dove.ranch.7GHz.otm	1-2,4,12,15-21,23-26,30-32
fishrite01	1,9-20
foothill.7GHz.otm	
foothill.7GHz.otm1	
foothill.7GHz.otm2	
hog.lake.4GHz.otm	
hoglake03.7GHz	
hoglake06.7GHz	snap 13 is TV, else stationary
otm1.multi	
otm2.multi	cluster variance $\approx -28dB$
otm3.multi	cluster variance $\approx -28dB$
rattrap.4GHz.otm	1-21
rattrap.4GHz.otm.1	1-23, 25-30
rattrap.7GHz.otm	1-31
rattrap.7GHz.otm.1	1-28
redbluff.otm1	1-3,5
redbluff01	1,3,4,6,7,9,12,13,16,20
runway.2ray.hh.otm	predominantly single-ray
runway.2ray.otm	snap 2 baud timing error
runway.shad.four.otm1	
ru.shd.1.otm	
rway.notch.otm.four	single ray, c. v. $\approx -29dB$
shadow.four.otm	
shadow.four.otm1	cluster variance $\approx -28dB$
shadow.four.otm2	cluster variance $\approx -28dB$
shadow.seven	snaps 5 & 28 timing error
Westover.7	1-12, 20-40
Westover.7.1	1-9,17-40

Table 3. Demodulation Errors

File	Comments	Miles
beegum.four.otm1	demod failed first snap	14
dibble.creek.otm	$\approx 26/32$ bad demods	26
hwy5-01	$\approx 19/20$ bad demods	33
oxbox.otm2	demod failed first snap	22
red.bluff.4MHz.otm	$\approx 14/16$ bad demods	34
red.bluff.4MHz.otm1	$\approx 11/16$ bad demods	34
red.bluff.7MHz.otm	$\approx 12/16$ bad demods	34
red.bluff.7MHz.otm1	$\approx 13/16$ bad demods	34
red.bluff.7MHz.otm2	$\approx 12/16$ bad demods	34
redbluff.otm	$\approx 12/16$ bad demods	32

tion Research Group at Cornell University in providing an empirically-derived database to study the time-varying effects on digitally modulated signals. Our efforts are by no means exhaustive, and we invite other researchers' comments and efforts regarding this data. Please notify us at **http://backhoe.ee.cornell.edu/BERG** if you access and use the database found at **http://spib.rice.edu/spib.html** in your research and development studies.

References

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