Signal Restoration and Channel Estimation for Channel Sounding with SDRs

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Outline

- Task
- Channel estimation procedure
- Unexpected effects
- Signal restoration algorithm
- Time-domain estimation considerations
- Results

Outline

Task

- Measure channel transfer functions and impulse responses using software-defined radios (SDRs) in place of more specialized hardware
- Transmitter: Ettus Research USRP B210
- Receiver: Ettus Research USRP N310

Channels

- Cable-bound transmission for test/calibration
- Wireless transmission, short-range line-of-sight channel
- Wireless transmission, longer-range non-line-of-sight channel

Outline

Signals

- Several repetitions of a Zadoff-Chu sequence of prime length 2557 are transmitted in order to determine the channel transfer function and from that the impulse response
- Zadoff-Chu sequences of prime length are of constant amplitude in both (discrete) time and frequency domain
- Zadoff-Chu sequences of prime length also have very good autocorrelation properties (CAZAC sequence: constant amplitude zero autocorrelation)
- Channel transfer function can be estimated simply by dividing the frequency domain of the received signal by the frequency domain of the sequence

Expected effects

- Delay / missing synchronization
- Carrier frequency offset (CFO)
- Noise (AWGN)
- Channel transfer function

Method

Problems

- Delay / missing synchronization
- Carrier frequency offset (CFO)
- Noise (AWGN)

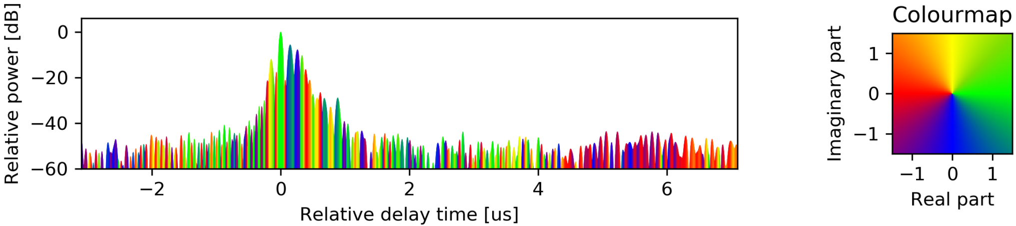
Solutions

- Find sequence in signal (correlation)
- Estimate and compensate CFO
- Average multiple received seqs.

Outline

Initial observations

- Artifacts visible in power delay profile

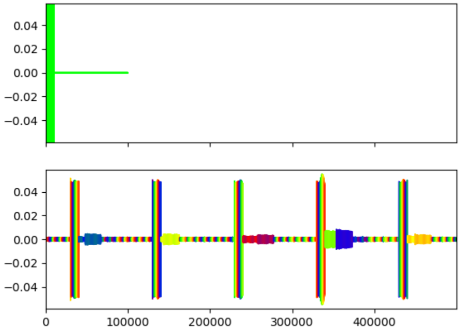


Estimated impulse response

- Inspection of raw data revealed several anomalies

Tests to determine nature of effects

- Changed waveform to simple square wave
- Also performed measurements with cable connecting transmitter and receiver



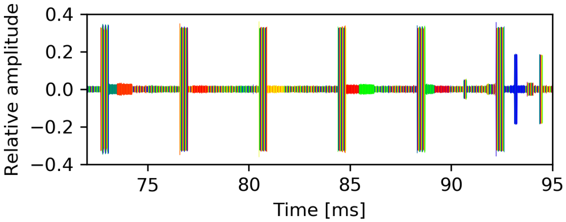
Transmitted and received signal (cable bound measurement)

Observable effects

- Random “blocks” appearing in the recorded signal
  - No CFO visible, implying that the blocks originate within the receiver
- CFO visible even when no signal is supposed to be transmitted
  - Visibility of CFO implies that this originates in the transmitter

$\Longrightarrow$ Transmitter must have some sort of zero offset

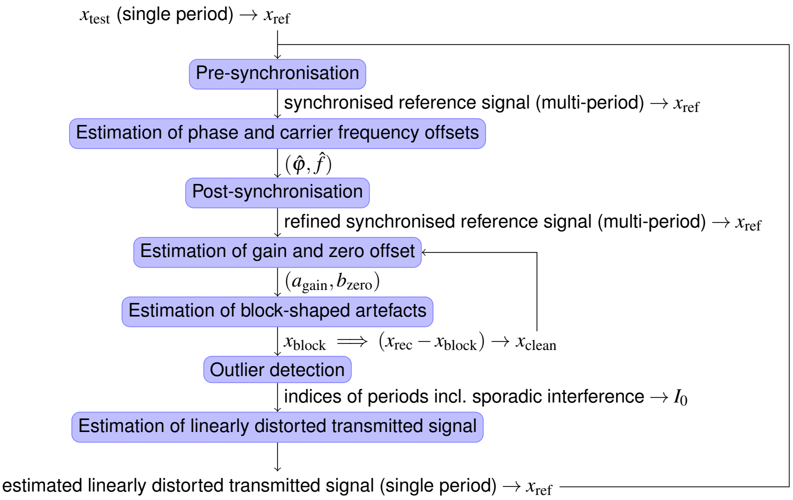
- In wireless measurements, also interfering signals from other sources



Received signal (wireless measurement)

Outline

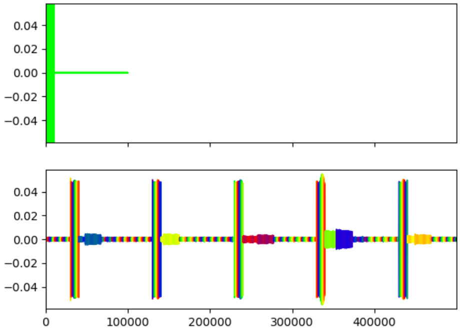
Signal restoration algorithm



Block diagram of signal restoration algorithm

Gain and zero offset estimation

- Estimate expected received signal by placing copies of the transmitted signal at positions where a signal was detected (initially)
- Use linear regression to estimate gain and zero offset
- This also provides an estimate of the expected received signal (albeit a very crude one) for later use

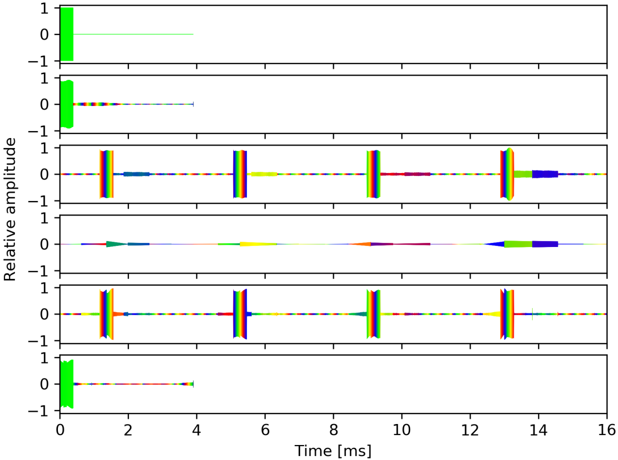


Transmitted and received signal
(cable bound measurement)

Removal of receiver-generated interference

- Received signal interferes with block estimation, so first subtract estimate of expected received signal from previous step (modulated with CFO) before estimating blocks
- Blocks are estimated via a two-stage procedure
- Starting with a rough estimate for block length, boundaries are estimated
- Value is assumed to be roughly linear across the entire duration of each block, values on first and last half are estimated and a linear interpolation/extrapolation procedure is applied
- “Some additional steps” are required in order to make estimation more robust

Removal of receiver-generated interference



Compensation of receiver-generated interference

Outlier detection

- Detect variations in energy of received signals
- A high energy value indicates the presence of some interfering signal
- When estimating the expected received signal, only use those segments which do not appear to have anomalous energy

Iterated procedure

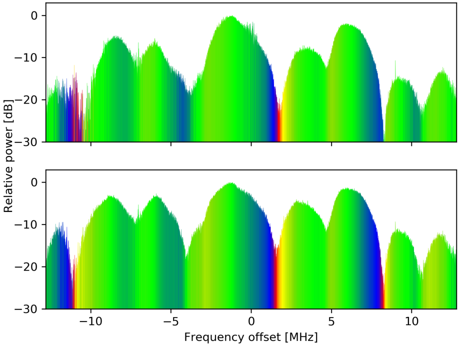
- To counter the above mentioned crudeness of the estimate of the received signal required to estimate gain, zero-offset, and receiver-generated interference, iterate the procedure
- In each iteration, the estimate for the expected received signal from the previous iteration is used to construct a better estimate

Iteration	Energy difference
0	4834.2995
1	0.007289
2	0.001858
3	0.001179
4	0.0006482
5	0.0002549
6	0.0011687
7	0.0011803
8	0.0011772
9	0.0006637
10	0.0007668
11	0.0006673
12	0.000001896
13	0.000001642
14	0.000002250
15	0.000001797
16	0.000002083
17	0.000002272
18	0.000002442
19	0.000002633

Energy difference between consecutive estimations, convergence of iterated procedure

Frequency domain comparison

- Different measurements were performed and the frequency domain representations were studied
- The plots shows the estimated channel transfer function of a non-line-of-sight channel
- The first plot is generated from the raw received signal, the second from the restored received signal
- The second plot is significantly smoother

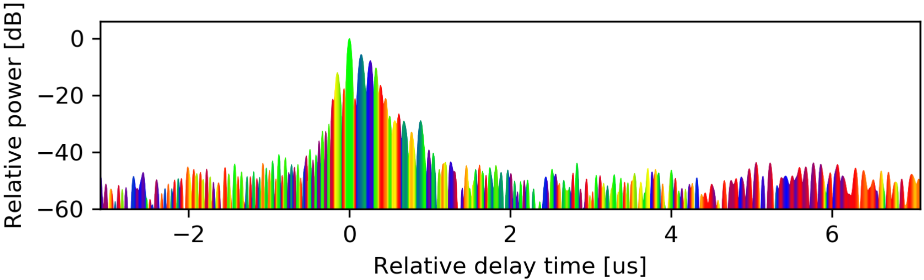


Comparison of estimated transfer functions

Outline

Upsampled time domain representation

- Use inverse Fast Fourier Transform (FFT) to obtain impulse response
- Applying zero padding to the frequency spectrum before the inverse FFT used to compute the impulse response leads to higher resolution in the time domain
- In the plot, several impulses surrounded by characteristic sinc-shaped tails are visible
- Suspicion: The pre-ringing observed in the impulse response estimates may be caused by these tails



Estimated impulse repsonse

Some background

- The channel sounding procedure simulates the transmission and reception of signals whose frequency domain consists solely of a finite linear combination of perfect impulses (pure tones)
- The channel transfer function acts as a multiplier on the frequencies at which these impulses are located
- The frequency domain of the recorded signal corresponds to the result of this multiplication

Some background

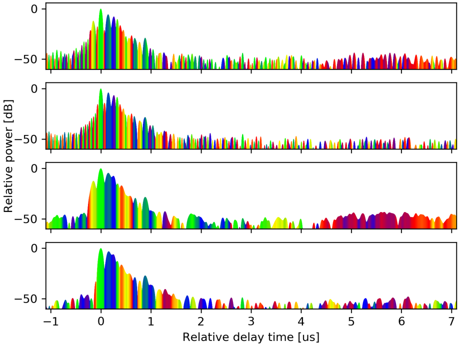
- However, when performing the inverse FFT, the frequency spectrum is regarded as a *periodic* function
- This leads to the observed artefacts
- The solution to this problem is two-fold:
  - Apply zero-padding to the frequency spectrum of the received signal to more closely approximate the true (aperiodic) channel transfer function
  - Apply a window function to the frequency spectrum of the received signal

  The latter of these two steps is required because the zero-padded frequency spectrum corresponds to a sampled channel transfer function multiplied by a rectangle, thus introducing sinc-shaped tails around impulses in the impulse response (multiplication by a rectangle corresponds to convolution by a sinc kernel)
- The window is chosen as a Dolph-Chebyshev window to minimize the amplitude of the residual tails

Outline

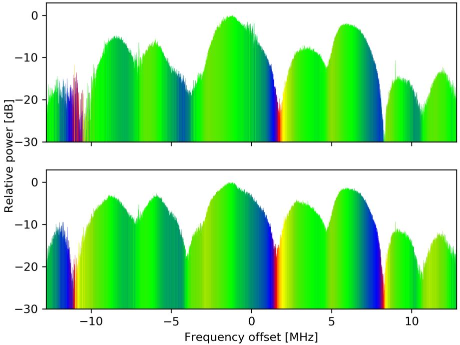
Results

- The figure on the right shows four different impulse response estimates:
  - Without restoration and frequency domain windowing (FDW)
  - With restoration but without FDW
  - Without restoration but with FDW
  - With restoration and FDW
- Comparison of the last two figures shows that the signal restoration algorithm was able to significantly improve SNR and eliminate a pre-echo
- Further measurements confirmed that the pre-echo must have originated from one of the measurement artefacts

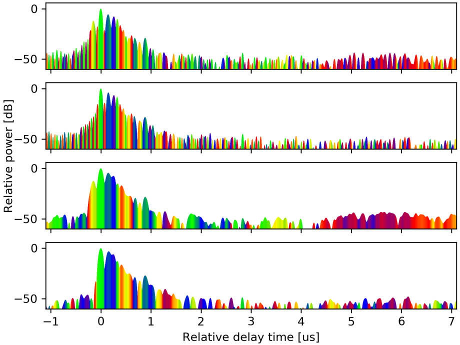


Effect of restoration and improved estimation procedure on impulse repsonse

Results



Effect of restoration on transfer function



Effect of restoration and improved estimation procedure on impulse repsonse

Questions?

Thank you!