Echo Cancellation in Digital Subscriber Line Systems

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Abbreviations

ADC ... Analog Digital Converter
ADSL ...Asymmetric Digital Subscriber Line
AEC ... Acoustic Echo Cancellation
DAC ... Digital Analog Converter
DSL ... Digital Subscriber Line

Abbreviations (ct.)

FIR ... Finite Impulse Response
FTTH ... Fiber-To-The-Home
LMS ... Least Mean Square
NEXT ... Near End Cross Talk Noise
POTS ... Plain Old Telephone Service
PSTN ... Public Switched Telephone Network
SNR ... Signal to Noise Ratio

Introduction - DSL

- DSL uses local loop of POTS
- Possible by using frequency band over speech band (300Hz to 3400Hz)
- DSL network consists of Central Office and DSL modem
- Using higher frequency band causes damping, available data rate depends on local loop length

Introduction - DSL (ct.)

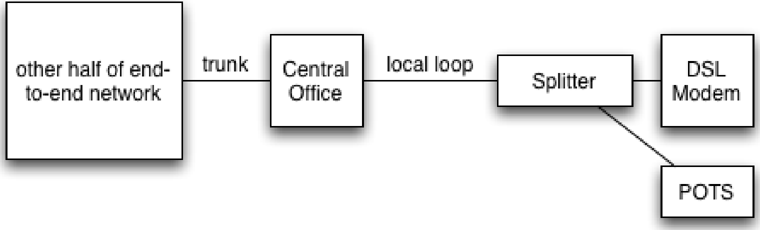

Figure: Typical DSL Network

Introduction - Adaptive Systems

- Conditions of telefon network change over time → adaptive filter
- Principle: start at a specified condition and find good approach by computing parameters iteratively
- Several algorithms exist, each for a special application field

Introduction - Adaptive Systems (ct.)

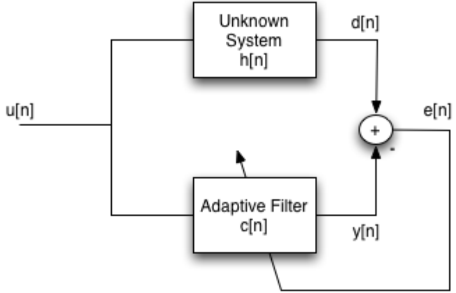

Figure: Adaptive System

Introduction - Adaptive Systems (ct.)

- Most common implementation uses LMS algorithm
- Adapts to minimum mean square error $J(c) = e[n]^2$
- Error surface is $N + 1$-dimensional paraboloid
- Optimal solution at bottom of bowl

Introduction - Adaptive Systems (ct.)

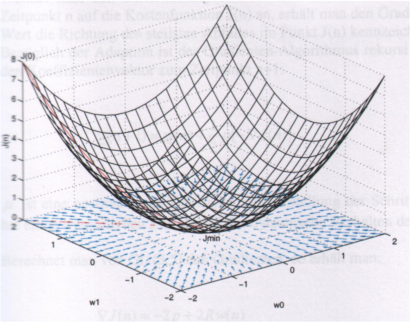

Figure: Mean Squared Error Surface ($N = 2$), taken from [6]

Introduction - Adaptive Systems (ct.) - The optimal Solution

- Initialize coefficient vector $c[n]$
- Go iteration step by computing negative gradient of mean square error
- Done long enough, coefficient vector converges to optimal solution
- Optimal solution at bottom of bowl

Introduction - Adaptive Systems (ct.)

The equations of the steepest descent are the following:

- $e[n] = y[n] - d[n]$
- $c[n+1] = c[n] + \frac{1}{2} * \mu * (-\nabla J(n))$

The Hybrid and the Echo Source

- In large distance systems we need four-wire transmission
- A hybrid is used to convert from two-wire to four-wire
- Hybrids ideally translate directly, but impedance mismatching problems
- This leads to coupling of energy from incoming to outgoing branch

The Hybrid and the Echo Source (ct.)

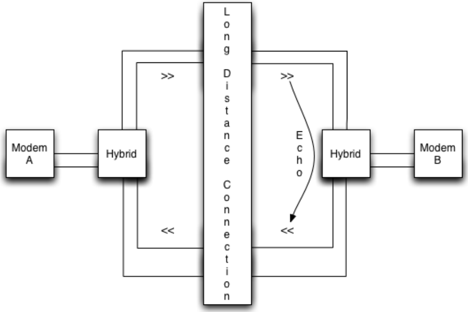

Figure: The Echo Source

Motivation of Echo Cancellation

- Full duplex operation
  - Split the passband in two separate channels
  - Upstream
  - Downstream
- Increase data transmission rates
  - Use the whole passband for both, transmission and reception
  - Transmission effects the reception
  - Remove effects through echo cancellation

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Echo Path Model and Canceller Requirements

- Data communication in full duplex mode
- Suiting echo cancellation techniques
- 60 *dB* of attenuation for properly working DSL tranceiver
- ADSL $\rightarrow$ different system at telephone subscriber side and central office side
- The following subsection are following corresponding parts in [3]

Echo Cancellation Requirements - The Echo Path

- Frequency division duplex systems
  - Passpand filters in series with the communication channel
  - Filtering out echo noise in spectra other than the signal
- Digital adaptive echo cancellers
  - Parallel to the system echo path.

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Echo Cancellation Requirements - The Echo Path (ct.)

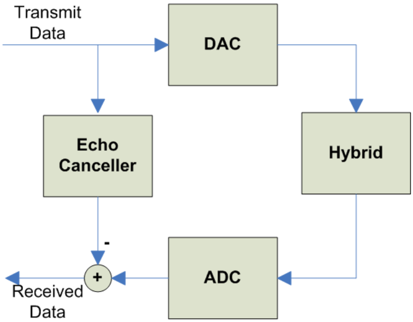

Figure: Echo Canceller

Echo Cancellation Requirements - The Echo Path (ct.)

- Goal of echo Cancellation:
  - Reproduce echo
  - Subtract echo from received signal
- Echo path transfer function is not frequency invariant
  - Frequency range up to 10^5 *Hz*: Echo return loss -6 *dB* to -24 *dB*
  - Low echo return loss at low frequencies caused by high impedances of twisted-pair loops
  - Low echo return loss at high frequencies due to leakage inductance in line transformers.

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Echo Cancellation Requirements - The Echo Path (ct.)

The average echo return loss is given by

- $K_{ep} = \frac{1}{f_c} \int_0^{f_c} |H_{ec}(f)|^2 \, df$
- $H_{ec}(f)$ ... echo path transfer function
- f_c ... corner frequency is the bandwidth of interest.
- Examples given in [3] find 18.5 dB for $f_c = 500\,kHz$ with the worst echo return at 6 dB as mentioned above.

Echo Cancellation Requirements - The Echo Path (ct.)

Introducing filters in the model

- $K_{ec} = \frac{1}{f_c} \int_0^{f_c} |G_t(f) H_{ec}(f) G_r(f)|^2 \, df$
- $G_t(f)$ ... transmit filter frequency response
- $G_r(f)$ ... receiver filter frequency response

Echo Cancellation Requirements - The Echo Path (ct.)

- Echo path impulse responses are quite different from system to system
- Common properties:
  - Rapidely changing start
  - Slowly decaying tails
- Due to:
  - Reflections caused by terminal impedance mismatches
  - Bridged taps in inital phase
  - Primary inductance causes slowly changing tail
- Consider round trip times - let initial reflections die out.

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Echo Cancellation Requirements - The Echo Path (ct.)

- RC-networks to model twisted-pair loop impedances
  - Conductance in series to a resistor
  - Resistor in parallel to these two
- ω_0 ... Resonant frequency
- α ... Damping factor
- Shorten the tail by a smaller primary inductance or a digital highpass $H(z) = 1 - z^{-1}$
- Removal of low frequency energy will influence the system performance in a NEXT dominated environment

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Echo Canceller Requirements

- Cancellation level: Echo cancellation quality measure
- Constraints on length of echo canceller possible
- Calculating the cancellation level:
  - $K_{EC} = SNR + K_{ch} - K_{ep}$
  - K_{ch} ... average channel loss
  - K_{ep} ... average echo path loss
  - SNR ... required signal-to-residual noise floor ratio

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Echo Canceller Requirements

Example

- $K_{ep} = 17\ dB$
- $K_{ch} = 23\ dB$
- $SNR = 44\ dB$
- K_{ec} around 60 dB for to be on the safe side

Echo Canceller Requirements(ct.)

- Having computed the required echo cancellation, we may now determine the time that has to be spanned
- $K_{EC} = -10 log_{10} \frac{\int_{t_s}^{\infty} h_{EC}^2(t)dt}{\int_0^{\infty} h_{EC}^2(t)dt}$ [3]
- The number of taps at a given input/output rate with t_s is determinde via K_{EC}
- ie.: 128 taps, 400kHz, $t_s < 320\mu s$

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- Echo canceller filter coefficients are estimated and updated using the LMS algorithm
- $H_{k+1} = H_k + \mu A_k(y(k) - H_k^T A_k)$
  - $y(k)$ ... Received signal
  - H ... Echo canceller filter
  - A ... Input Signal
- They are trained in half duplex mode at startup for faster convergence
  - $\mu_{opt} \leq \frac{1}{mE[a_k^2]}$
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Echo Cancellation Requirements - The Echo Path (ct.)

- Precision requirement
- Processing in full duplex mode while working with small step sizes still do adaption of filter coefficients
- In a useful setup the noise (its variance) introduced by the filter must not be larger than that one introduced by devices like the ADC
  - Converters introduce nonlinearities
  - $\sigma^2_{A/D} = \frac{1}{3}\frac{1}{2^{2N}}$
- $\sigma^2_{filter} = m\frac{1}{3}\frac{1}{2^{2M}}$
  - m ... number of coefficients for canceller
  - M ... canceller coefficient resolution
- Bounded by: $M \geq N + \frac{1}{2}log_2 m$

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Asymmetrical Cancellation

- Different conditions at central office and telephone subscriber side
- Due to asymmetrical throughput conditions, transmit spectra and different sampling rates
- Well known example:
  - ADSL is a typical setup where different sides of the system require different echo cancellers

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Cancellation Algorithms for Data Transmission

- [2] compares AEC to echo cancellation in Data Transmission and is somewhat based on Material that can be found in [1]
- The text below will focus on parts dealing with Data Transmission

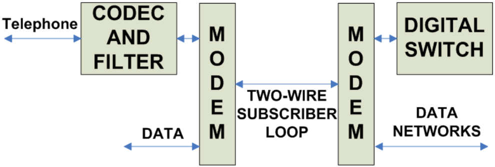

Figure: Application

Cancellation Algorithms for Data Transmission (ct.)

- Data transmission is mainly done on two wire connections due to high cost of copper wire
- For an overview of alternative technologies [4] talks about different solutions:
  - FTTH
  - Coax or Fiber-Coax-Hybrids
  - Wireless Systems
  - Satellite Services

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Cancellation Algorithms for Data Transmission (ct.)

- Motivation:
  - Assuming 10 *dB* of attenuation of feedthrough of the hybrid due to lacking knowledge of two-wire impedance
  - 50 *dB* channel loss and equal signal power on both sides of the line
  - Local feedthrough (echo) would be 40 *dB* higher than the signal to be received
  - Aiming for 20 *dB* SNR we have to attenuate the echo by 60 *dB*

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Cancellation Algorithms for Data Transmission (ct.)

- Timing constraints - different sampling rates at input and output
- Transmitted signal: $s(t) = \sum_m C_m g(t - mT)$
  - $g(t)$ ... transmitted pulse shape
  - C_m ... transmitted data symbols
  - T ...time between two symbols
- Passing signal through a filter with echo response H_e
  - rewrite $s(t)$ to $r(t)$ as the filter respone to $s(t)$
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Cancellation Algorithms for Data Transmission (ct.)

Reconstruction of this signal

- For an integer multiple of T as RT we define
  - $r_l(l) = r((i + \frac{l}{R})T)$
  - i ... the data symbol epoch
  - l from 0 to $R-1$ represents the sample chosen in this epoch

Cancellation Algorithms for Data Transmission (ct.)

- Redefine the echo pulse response to generate the replica
  - $h_i(l) = h((i + \frac{l}{R})T)$ ... $0 \leq l \leq R - 1$
  - $r_i(l) = \sum_m h_m(l) C_{i-m}$ ... as samples of the received echo
- This FIR filter approximates the echo response
- R independent cancellers that will get the same reference input within an symbol epoch
  - $r_i = \sum_{m=0}^{n-1} C_{i-m} a_m$ ... $0 \leq i < n - 1$ ... a as filter coefficients

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Cancellation Algorithms for Data Transmission (ct.)

Example setup

- Receive far-end data plus hybrid-echo
- Decimate this input down to R signals at symbol data rate
- Cancel the echo independently in each channel
- Receive the far-end data after recombination of channels

Design Considerations

- Trade-off: Speed of Adaption vs. Accuracy of Cancellation
- These two goals typically counteract:
  - Asymptotic behavior: *'Inverse of Speed of Adaption'*
- Important: fast startup
  - Echo path transfer function will not vary too fast
- Speed of echo cancellers might not be too critical
- Ie.: It is possible to implement simple stochastic gradient descent algorithms

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Design Considerations (ct.)

Notation

- Filter coefficients: $a^T = [a_0, a_1, ..., a_{n-1}]$
- Reference input: $y_i^T = [y_i, y_{i-1}, ..., y_{i-n+1}]$
- Echo path impulse response: $h^T = [h_0, h_1, ..., h_{n-1}]$
- Received signal: x
- Uncancable error (echo with delay exceeding the number of canceller coefficients: $v_k = \sum_{m=n}^{\infty} h_m y_{k-m} + x_k$
- Canceller error: $e_k = \sum_{m=0}^{\infty} h_m y_{k-m} - \sum_{m=0}^{n-1} a_m y_{k-m} + x_k = (h-a) y_k + v_k$

Design Considerations (ct.)

Notation

- Assuming the reference signal y_i and the near-end talker v_i to be jointly wide-sense stationary
  - $p = E[v_i y_i]$, $\Phi = E[y_i y_i^T]$, $R_j = E[y_i y_{i+j}]$
- Minimizing $E[e_i^2]$
  - $a_{opt} = h + \Phi^{-1} p$
  - $\Phi = R_0 I$ ... I is the identity matrix
- $p = 0$ ... with mutually uncorrelated reference samples, without correlation of reference and received signal:
- $a_{opt} = h$

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Design Considerations (ct.)

- $a_{opt} = h$
- Coming close to that by choosing the number of coefficients large enough
- The most common algorithm for cancellers are stochastic gradient algorithms (LMS)
- Assuming knowledge about statistics of reference and near-end-talker one can avoid matrix inversion by iterative gradient algorithm

Design Considerations (ct.)

- Expectation is usually not known in practice
  - So we leave it out
- The replacing quantity has the same Expectation
  - But it is a different random variable
  - So the estimation is unbiased but noisy
- Stochastic gradient algorithm:
  - $a_i = a_{i-1} - \frac{\beta}{2}\nabla_a[e_i^2]$ ... β is the step size for convergence control
  - $a_i = a_{i-1} + \beta e_i y_i = (I - \beta y_i y_i^T)a_i + \beta(y_i y_i^T h + v_i y_i)$

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- Via coefficient vector trajectories one can define the evolution of the error over iterations
- Evaluating this approach one will find that there are several constraints for the matrix
    - $\Phi = R_0 I$ with $R_j = E[y_i y_{i+j}]$:
    - symmetric
    - Toeplitz(Toeplitz matrix is a matrix which has constant values along negative-sloping diagonals)
    - positiv definite($\Re[x^* Ax] > 0$)
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Design Considerations (ct.)

- $\lambda_{max} \rightarrow maxS(\omega)$
- $\lambda_{min} \rightarrow minS(\omega)$
  - A large ratio between maximum and minimum spectrum of the reference signal leads to slow convergence of average coefficient vector trajectories
  - A small ratio lets the trajectories converge fast
  - For the theory of fluctuation of trajectories about the average [1] gives a detailed analysis
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- Derived in the paper [2]
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Further Adjustments

Nonlinear Echo Cancellation

- The algorithm presented deals with echo path impulse reponses as linear combination of the reference signal
- Converters are the main sources for nonlinear noise
  - Small variance, but has to be taken into account
  - 60 *dB* of cancellation is targetet

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Nonlinear Echo Cancellation

- Detailed analysis in [1]
  - Volterra series can be shown to be capable of providing perfect cancellation
  - Finite number of filter coefficients
  - Assumes that the echo can be represented as a function of a finite number of past transmitted data symbols [2]

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Adaption Speedup

- Fast initial convergence through large β
- Using lattice filter structures
  - No guarantee to find good solutions for every case
  - Whitenes the reference signal $\Rightarrow$ introduces some dependency on the input that can be hard to deal with

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Further Adjustments

Adaption Speedup

- Kalman filters
  - Fast initial convergence
  - Able to deal with uniformly distributed noise from the converters
  - Might be hard to meet all requirements for kalman filtering theory

Conclusion

- Several aspects to be considered
- Some theoretical background for parts of the problem in literature
- Main focus on Cancellation in Speech Transmission

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Thank you for your attention!

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Feel free to ask quesitons!