Channel Estimation of LTE Downlink in High Speed Environment

Xuewu Dai
Dept. of Electronic and Electrical Engineering, UCL
Dept. of Engineering Science, University of Oxford
Email: xuewu.dai@eng.ox.ac.uk

Yang Yang (WiCO)
John Mitchell (UCL)
Outline

1. Introduction
2. Channel model & LTE OFDM reception
3. Extended Kalman Filter (EKF)
   - augmented state space model
   - EKF for channel estimation
   - EKF for channel interpolation
4. Implementation consideration
5. Simulation results
6. Summary
Motivation

• Future network aiming at improved mobility and certain QoS guarantees.
• within current LTE specifications, the description of UE speed is <120kmph
• LTE at velocity up to 350kmph is desired.
• Challenges in high-mobility applications (e.g. high speed train)
  
  low sensitivity to high speed (the Doppler effect)

  fast switch
Wireless channels in high speed environment

Time-varying channel transfer function

\[ g(\tau) = \sum_{n=1}^{R} \alpha_n \cdot \delta(\tau - \tau_n) \]

(b) low Delay Spread and high

Ref: Muhammad Saad Akram, *Pilot-based Channel Estimation in OFDM Systems*, Nokia Mobile Phones
QAM system and channel estimation

represented as a baseband channel model
2. LTE reception and Channel model

Pilot-symbol assisted modulation (PSAM) in LTE/OFDM

- Known OFDM symbol, so-called pilots or reference symbols are inserted into the data stream
- Three kind of Time-Frequency allocation of pilot symbols: block pilot, pilot subcarriers and scattered pilots

LTE downlink frame structure with scattered pilots
2. LTE reception and Channel model

Pilot-aided channel estimation
1. Channel estimation at the pilot symbol location
2. Time-domain interpolation
3. Frequency-domain interpolation
2. Channel model and LTE reception

• 2.1 Multi-path Time-varying channel model

\[ g(t, \tau) = \sum_{l=0}^{L-1} \alpha_l(t) \delta(\tau - \tau_l) \]

**Channel Impulse Response (CIR)**

\[ g_k = [g_{k,0} \ g_{k,1} \ \cdots \ g_{k,L-1}]^T \]

**Channel Frequency Response (CFR)**

\[ \bar{h}_k = [h_k[1] \ h_k[2] \ \cdots \ h_k[N]]^T \]

\[ h_{k+1,n} = a_n h_{k,n} + \nu_{k,n} \]

• An AR model describes the time variation of \( h_k[n] \)
• \( h_k[n] \): channel attenuation to be estimated at the k-th OFDM symbol and at n-th subcarrier.
2.2 LTE OFDM reception

The received signal:
\[ y_k = X_k h_k + w_k \]

\[ X_k = \text{diag}(x_k) = \begin{bmatrix} x_{k,1} & 0 & 0 & \ldots & 0 \\ 0 & x_{k,2} & 0 & \ldots & 0 \\ 0 & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \ldots & x_{k,N_p} \end{bmatrix} \]

- LTE OFDM Channel equaliser:
\[ \hat{x}_{k,n} = y_{k,n} / h_{k,n} \]

- Goal of channel estimation:
\[ \arg \min_h \sum_k \| x_k - y_k \cdot h_k \|_2 \]

- Key issue: how to get the right value of \( h_{k,n} \)
3. Extended Kalman Filter (EKF) for LTE channel estimation

\[
\begin{align*}
    h_{k+1} &= A_k h_k + v_k \\
    y_k &= X_k h_k + w_k
\end{align*}
\]

- \( h_k \) is the unknown CFR
- \( A_k \) is the parameters representing the time correlation coefficients of CFR
- \( V_k \) represents the channel modelling error
- \( W_k \) is the noise in the channel
- Estimate \( h_k \) and \( A_k \) from the received \( y_k \) (fully known) and the transmitted \( X_k \) (partially known at pilot location only)
Augmented model

- A non-linear problem:

  to simultaneously estimate both $h_k$ and $A_k$

  $$
  \begin{align*}
  a_{k+1} &= a_k + \epsilon_k \\
  h_{k+1} &= A(a_k)h_k + v_k \\
  y_{k+1} &= X_k h_k + w_k
  \end{align*}
  $$

  $$
  z_k = \begin{bmatrix} a_k^T & h_k^T \end{bmatrix}^T
  $$

  $$
  \begin{align*}
  z_{k+1} &= f(z_k) + u_k \\
  y_k &= \begin{bmatrix} 0_{1 \times N_A} & X_k \end{bmatrix} z_k + w_k
  \end{align*}
  $$

  and

  $$
  f(z_k) = \begin{bmatrix} a_k \\
  A(a_k)h_k \end{bmatrix}
  $$

  linearisation

  $$
  \begin{align*}
  z_{k+1} &= F_k z_k + u_k \\
  y_k &= \begin{bmatrix} 0 & X_k \end{bmatrix} z_k + w_k
  \end{align*}
  $$

  and

  $$
  F_n = \begin{bmatrix} I_{N_A} & 0 \\
  \hat{H}_{n|n} & \hat{A}_{n|n} \end{bmatrix}
  $$

A joint state and parameter estimation.
EKF for channel estimation

1. Prediction: Estimate a priori \( k \)-th CFR \( \hat{h}_k \) from \( (k-1) \)-th channel estimation \( \hat{h}_{k-1} \) before receiving a OFDM symbol.

2. Correction: Correct the a priori \( k \)-th CFR \( \hat{h}_k \) by using the received OFDM symbol to get a better a posteriori \( k \)-th CFR \( \hat{h}_k \).
EKF for channel interpolation
a decision-directed approach

For the pilot symbol, the transmitted symbol $x_k$ is known, use $x_k$ for channel estimation.

For the data symbol, the transmitted symbol $x_k$ is unknown, use the decoded $\hat{x}_k$ for channel estimation.
4. Implementation consideration

• **Initialisation: by Least Squares Estimation**

\[
\hat{h}_{0,LS} = (X_0^H X_0)^{-1} X_0^H y_0
\]

\[
= \left[ \frac{y_{0,1}}{x_{0,1}}, \frac{y_{0,2}}{x_{0,2}}, \ldots, \frac{y_{0,N_p}}{x_{0,N_p}} \right]
\]

Selection of the covariance matrices for channel (measurement) noise $W_k$

\[
\sigma_w^2 = \frac{P_{tx}}{10^{SNR/10}}
\]
5. Simulation results

1. Channel configuration:
   a rural area channel model defined by 3GPP

2. 512 subcarriers of which 300 are for data transmission.
3. Two speeds of user equipment (UE) 50 and 200 km/h
4. SNR varying from 0 to 40 dB at a step size of 5 dB.
5. Repeated 20 times (20 runs) at each SNR
Channel estimation Error

Left: by the EKF; right: by the least square estimation
Mean square estimation error

Average Estimation Errors v.s. SNRs (200km/h)

Magnitude of Estimation Errors

SNRs (dB)

LS -200km/h
EKF -200km/h
BER performances

- Left: 50km/h;
- the EKF interpolation filter improved the LS
- In Particular, a SNR gain up to 8 dB obtained for certain BERs (e.g. 0.002) at high-velocity.

Right: 200km/h
6. Summary

- The time-varying radio channel is modeled as an AR process presented as an state space form.
- An extended Kalman filter is developed for both
  1. channel estimation at pilot symbols
  2. interpolation at data symbols
- A significant improvement of BER performance
- Future work for further improvement: initialised by MMSE, etc.
  error propagation in decision-directed mode
Thanks & Questions ?