Channel Prediction for Link Adaptation in LTE Uplink

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Abstract— **Link adaptation is the process of selecting Modulation and Coding Scheme (MCS) and Precoder Matrix Index (PMI) based on channel quality measures. Here a Signal to Interference and Noise Ratio (SINR) estimate is used as quality measure, which is calculated from channel and noise covariance estimates. An SINR expression is derived within the current paper which is designed for a Minimum Mean Square Error (MMSE) equalizer with a single tap channel model, which is an equalizer suitable for uplink Long Term Evolution (LTE). Channel estimates from Sounding Reference Signal (SRS) are used for this link adaptation. Illustrations are given in the current paper of the performance impact of the time delay between transmissions of SRS to the time instant when the result of the link adaptation is used. Furthermore, a channel predictor is proposed in order to reduce the impact of this delay. Simulations results indicate the benefits of using the proposed channel predictor, in terms of link level throughput.**

Keywords- link adaptation, channel prediction, LTE, MIMO, Wiener-Hopf, MMSE equalizer, post demodulation channel, SINR estimation

I. INTRODUCTION

Radio Resource Management (RRM) is a system level control in the base-station (eNodeB in LTE vocabulary) of radio resources such as user scheduling, link adaptation, handover, and transmit-power, see Figure 1. A user scheduler selects time, frequency intervals and spatial resources in which each user is allowed to transmit. The link adaptation includes selection of the MCS that each User Equipment (UE) should use. Several modulations (such as QPSK, 16QAM and 64QAM) and coding rates are allowed for LTE [1]. Also, with closed loop pre-coding, the eNodeB is selecting a Precoder Matrix Index (PMI) i.e. transmission rank and which pre-coder (out of a set of predefined alternatives) which a UE should use for transmissions in uplink [1].

For MIMO in LTE uplink, both user data and the Demodulation Reference Signals (DRS) [1] are precoded by a precoder as selected by the eNodeB. Thus, these reference signals can not be used for selection of precoders for future transmissions. Instead the Sounding Reference Signals (SRS) [1] are used for channel quality measurements, see Figure 1. The SRS transmissions typically span a larger frequency interval than the user data and are not pre-coded. Also, these SRS transmissions can be configured to be transmitted in a periodic manner ranging from each second sub-frame (2 milliseconds) up to each 320^{th} sub-frame [3].

The link adaptation results in selection of one MCS index out of a predefined set of allowed schemes, see [3]. By transmitting the MCS index on a downlink control channel (the Physical Downlink Control Channel, PDCCH), the UE knows which modulation and coding to use when transmitting uplink data (on the Physical Uplink Shared Channel, PUSCH), see Figure 1. The PUSCH has a Transmission Time Interval (TTI) of one millisecond (i.e. one sub-frame).

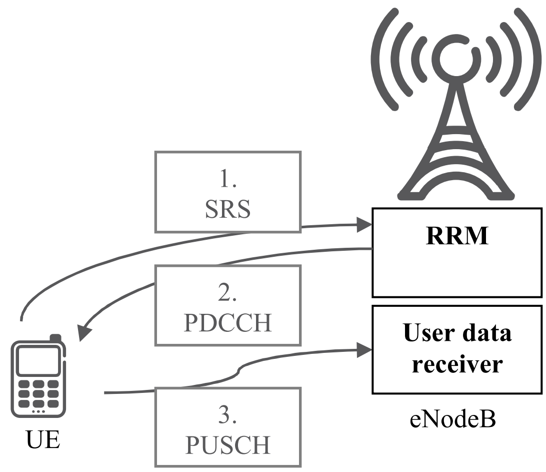

Figure 1. RRM and user data receiver in eNodeB.

From the channel quality measurement on SRS to transmission of DPCCH, the RRM needs at least one millisecond for processing. The delay from PDCCH to PUSCH is 4 milliseconds according to [3]. Thus, the total delay is at least 5 milliseconds from channel measurements (on SRS) to the use of the link adaptation (on PUSCH). When the SRS is configured to be transmitted with a period of once each 10^{th} millisecond, this delay is thus ranging from 5 up to 14 milliseconds, resulting in somewhat outdated measurements. For medium to small Doppler spreads, the channel can be predicted by using several SRS observations, as will be described in section II.B.

A schematic illustration of a demodulator (user data receiver) for LTE uplink and the link adaptation part of the RRM is given in Figure 2. Here, a radio front end is given as an FFT followed by channel estimation. The demodulator is including the DRS channel estimation [5][6][7]), equalizer (see e.g. [8]), IDFT (due to DFT precoded OFDM used for LTE uplink [1]), symbol de-mapping and decoding (reverse of [2]).

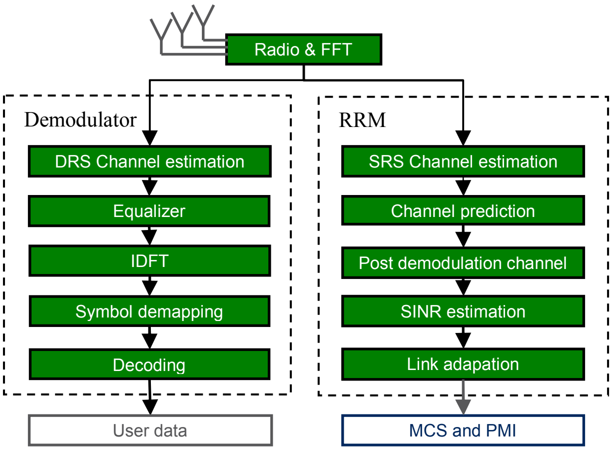

Figure 2. Link adaptation and demodulator structure.

Within the RRM only the link adaptation is included in Figure 2, which is also an illustration the outline of section II. Here, the SRS channel estimation is described in section II.A, the channel prediction in section II.B, the post demodulation channel in section II.C, the SINR estimation in II.D and the link adaptation in section II.E. The paper concludes with simulation results in section III and conclusions in section IV.

II. LINK ADAPTATION OUTLINE

A. SRS channel estimation

Channel estimation can for example be done as proposed in [5][6], or [7]. The channel estimate for link adaptation is based on SRS and is modeled as

$$\hat{H}(m,n) = H(m,n) + N(m,n)$$
$$= \begin{bmatrix} \hat{h}_{0,0}(m,n) & \hat{h}_{0,1}(m,n) & \cdots & \hat{h}_{0,L-1}(m,n) \\ \hat{h}_{1,0}(m,n) & \hat{h}_{1,1}(m,n) & & \\ \vdots & & \ddots & \\ \hat{h}_{K-1,0}(m,n) & & & \hat{h}_{K-1,L-1}(m,n) \end{bmatrix} \quad (1)$$

for K antennas and L layers, sub-carrier $m = 0,\ldots,N_c - 1$ and time index n where $H(m,n)$ denotes true channel and $N(m,n)$ denotes additive noise with covariance matrix

$$\Lambda = E\{N(m,n)N^*(m,n)\} = \begin{bmatrix} \lambda_{0,0} & \lambda_{0,1} & & \lambda_{0,K-1} \\ \lambda_{1,0} & \lambda_{1,1} & & \\ & & & \\ \lambda_{K-1,0} & & & \lambda_{K-1,K-1} \end{bmatrix}$$

and where * denotes conjugate and transpose.

B. Channel prediction

When the UEs are moving, or when there is an uncompensated frequency error, the channel from the UE to the base-station will be time varying. Then, the output from an SRS channel estimator will deviate from the channel at the time instant when PUSCH is transmitted over the channel.

The link adaptation should be based on the channel at the time instant for transmission. In order to estimate the channel in this future time instant with a good accuracy, an averaging over several channel estimates and prediction can be done as described below.

Denote the predicted channel matrix as $\hat{H}(m,n+t_P|n)$ for sub-carrier m and time $n+t_P$ based on measurements up to time instant n. A FIR (Finite Impulse Response) prediction $\hat{H}(m,n+t_P|n)$ for the channel, in row i and column j of $H(m,n+t_P)$, can be written as

$$\hat{h}_{i,j}(m,n+t_P|n) = \theta^{(i,j)^T}\varphi^{(i,j)}(m,n) \quad (2)$$

where

$$\varphi^{(i,j)}(m,n) = \left[\hat{h}_{i,j}(m,n-t_0) \quad \ldots \quad \hat{h}_{i,j}(m,n-t_{M-1})\right]^T \quad (3)$$

and where the coefficients in $\theta^{(i,j)^T}$, which can be pre-calculated, depend on

- measurements instants $t_0, t_1, \ldots, t_{M-1}$ with $t_0 = 0$
- prediction horizon t_P
- Doppler Spread
- Signal to Noise Ratio.

Optimal FIR channel prediction coefficients can be calculated as [9][10]:

$$\theta^{(i,j)} = \left[\theta_0^{(i,j)} \quad \theta_1^{(i,j)} \quad \ldots \quad \theta_{M-1}^{(i,j)}\right]^T = R_{\varphi}^{(i,j)^{-1}} r_{h\varphi}^{(i,j)} \quad (4)$$

a.k.a. the classical Wiener-Hopf equations, which minimize the mean square error

$$E\left\{h_{i,j}(m,n+t_P) - \theta^{(i,j)^T}\varphi^{(i,j)}(m,n)\right\} \quad (5)$$

where

$$R_{\varphi}^{(i,j)} = \left(\frac{\sigma_{h,i,j}^2}{\lambda_{i,i}}\right)^{-1} I + \begin{bmatrix} J_0(0) & J_0(-2\pi f_D t_1) & \dots & J_0(-2\pi f_D t_{M-1}) \\ J_0(2\pi f_D t_1) & J_0(0) & & \\ & & & \vdots \\ J_0(2\pi f_D t_{M-1}) & & \dots & J_0(0) \end{bmatrix} \quad (6)$$

with channel variance $\sigma_{h,i,j}^2$,

$$r_{h\varphi}^{(i,j)} = \left[J_0(2\pi f_D(t_P+0)) \quad \dots \quad J_0(2\pi f_D(t_P+t_{M-1}))\right]^T \quad (7)$$

and $J_0(2\pi f_D t)$ is the zero order Bessel function of first kind with Doppler spread f_D. Here, $\sigma_{h,i,j}^2/\lambda_{i,i}$ is the SNR of the channel estimate which is considered as a design variable of the channel predictor. A low value of this channel SNR can be used in order to slow down and reduce the variance of the channel predictor.

C. Post demodulation channel and noise covariance matrix

The channel estimate provided by the channel predictor is converted to a post demodulation channel within this section. This processing is done in order to mimic the receiver to be used when the PUSCH is demodulated. With an MMSE equalizer for LTE uplink, the post-demodulation channel includes

- Impact of "orthogonality" between the channels of the MIMO layers
- Channel attenuation
- Impact of tradeoff between zero forcing and matched filter i.e. the MMSE equalization
- Impact of inter-symbol-interference
- Noise variance after MMSE

A frequency dependent MMSE weighting matrix can be calculated as

$$W(m) = (\hat{\Lambda} + \hat{H}(m)\hat{H}^*(m))^{-1}\hat{H}(m) \quad (8)$$

where $\hat{\Lambda}$ is an estimated noise covariance matrix and $\hat{H}(m) = \hat{H}(m, n+t_P|n)$ is a predicted channel matrix from the channel predictor for frequency index m (where the time dependency is omitted for brevity). The predicted channel matrix is then multiplied with this frequency dependent weighting matrix resulting in a predicted frequency domain post demodulation channel

$$\widetilde{H}(m) = W^*(m)\hat{H}(m). \quad (9)$$

Since the modulated symbols transmitted on the uplink is pre-coded by a DFT [1] the channel after MMSE combining and equalization must be transformed to the time domain by an IDFT [8]

$$\widetilde{G} = \begin{bmatrix} \widetilde{g}_{0,0} & \widetilde{g}_{0,1} & \cdots & \widetilde{g}_{0,L-1} \\ \widetilde{g}_{1,0} & \widetilde{g}_{1,1} & & \\ \vdots & & \ddots & \\ \widetilde{g}_{L-1,0} & & & \widetilde{g}_{L-1,L-1} \end{bmatrix} = \frac{1}{N_c}\sum_{m=0}^{N_c-1}\widetilde{H}(m) \quad (10)$$

which is an IDFT evaluated at time lag zero. This is the channel at time lag zero which is motivating the expression of a "single tap channel model" in the MMSE equalizer.

The residual noise after MMSE contains two components; additive noise filtered though the MMSE combining weights, and inter-symbol interference. An estimate of this filtered noise covariance matrix equals

$$\Lambda_N = \sum_{m=0}^{N_c-1} W^*(m)\hat{\Lambda}W(m) \quad (11)$$

where $\hat{\Lambda}$ is the estimated noise covariance matrix from the channel estimator and $W(m)$ are the MMSE combining matrices. The inter-symbol interference covariance matrix equals

$$\Lambda_{ISI} = \sum_{m=0}^{N_c-1}(\widetilde{H}(m)-\widetilde{G})(\widetilde{H}(m)-\widetilde{G})^*. \quad (12)$$

In total, the residual noise covariance equals

$$\widetilde{\Lambda} = \Lambda_N + \Lambda_{ISI} = \begin{bmatrix} \widetilde{\lambda}_{0,0} & \widetilde{\lambda}_{0,1} & \widetilde{\lambda}_{0,L-1} \\ \widetilde{\lambda}_{1,0} & \widetilde{\lambda}_{1,1} & \\ & & \\ \widetilde{\lambda}_{L-1,0} & & \widetilde{\lambda}_{L-1,L-1} \end{bmatrix}. \quad (13)$$

The "predicted post demodulation channel" matrix $\widetilde{G}$ and "post demodulation noise covariance" matrix $\widetilde{\Lambda}$ are then used in the SINR calculation as described below.

D. Signal to Noise and Interference Ratio (SINR)

When calculating the SINR, the predicted channel after equalization of the desired layer is used in the numerator and all other layers plus residual noise in denominator.

For layer number k, a post demodulation SINR is accordingly calculated as

$$\Delta_k = \frac{\left|\widetilde{g}_{k,k}\right|^2}{\widetilde{\lambda}_{k,k} + \sum_{\substack{i=0 \\ i\neq k}}^{L-1}\left|\widetilde{g}_{k,i}\right|^2}. \quad (14)$$

In this post demodulation SINR equation, the predicted channel and noise variance after MMSE equalization is used, i.e. the predicted post demodulation channel.

E. Link adaptation

The SINR as calculated in the previous section is used in a table look-up for link adaptation. Alternatively, the SINR can be re-calculated to a mutual information measure which can be further processed, e.g. averaged, before link adaptation look-up table.

By simulations, the SNR required to reach a specific Block Error Rate (BLER) can be determined for a number of coding rates. This is illustrated in Figure 3 for a BLER of 3% for each of the three modulations supported by LTE, i.e. QPSK (blue dashed), 16QAM (blue dash-dot) and 64QAM (blue solid). Here a simulation setup is used such that the impact of receiver characteristic is low, i.e.

- AWGN channel => No Inter Symbol Interference,
- AWGN channel => No MMSE equalization effect
- Single user and layer => No interference
- Single antenna => No antenna gain

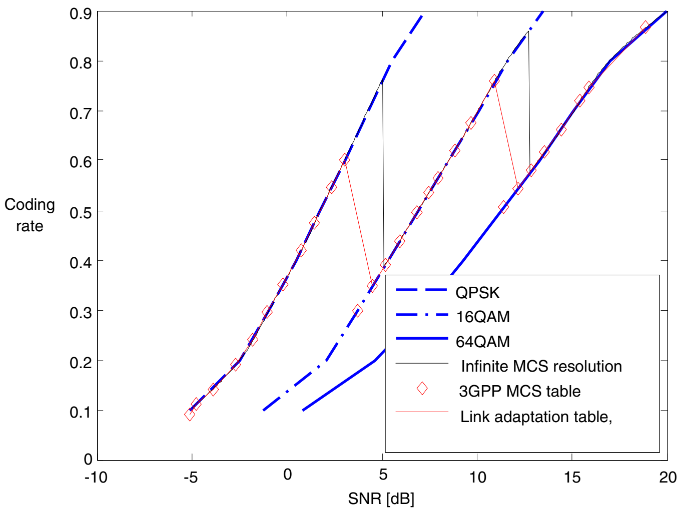

Figure 3. Link adaptation illustration with coding rate versus SNR for 3% BLER with QPSK, 16QAM and 64QAM.

Modulation and Coding Schemes (MCS) supported in 3GPP [3] are marked with red diamonds in Figure 3 for QPSK, 16QAM and 64QAM. A red solid line is used as illustration of the MCS values to be used in the link adaptation. This Figure 3 is thus an illustration of the link adaptation where the SNR for each MCS illustrates the lower limit for the post demodulation SINR where an MCS should be used.

III. SIMULATIONS

Performance simulations of uplink LTE is given in this section, in terms of user throughput (bits per second). The channel was simulated with an Extended Vehicular A (EVA) model [8] with 5 Hz Doppler spread on a system bandwidth of 20 MHz. The user was allocated 720 kHz which corresponds to 4 Resource Blocks (RB) within LTE vocabulary. Each UE is transmitting using 2 antennas. A Hybrid Automatic Repeat reQuest (HARQ) with a maximum of 5 transmissions is also used. In the current report, ideal channel estimates are used in all simulations but on positions in time corresponding to transmissions of SRS. Also, the Doppler spread is assumed to be known in the design of the Wiener-Hopf predictor where $M = 10$ coefficients are used.

Examples of channel realizations for a 2x2 MIMO system is given by blue dots in Figure 4 and Figure 6, where the channel is sampled once each millisecond, which is the same rate as the TTIs in LTE uplink. The channels at the SRS transmissions are illustrated by red x-marks, once each 10^{th} millisecond. A "delayed channel" predictor is also illustrated in Figure 4 with black diamonds. This is the baseline predictor which will be used to compare the results of using the Wiener-Hopf predictor as discussed in section II.B.

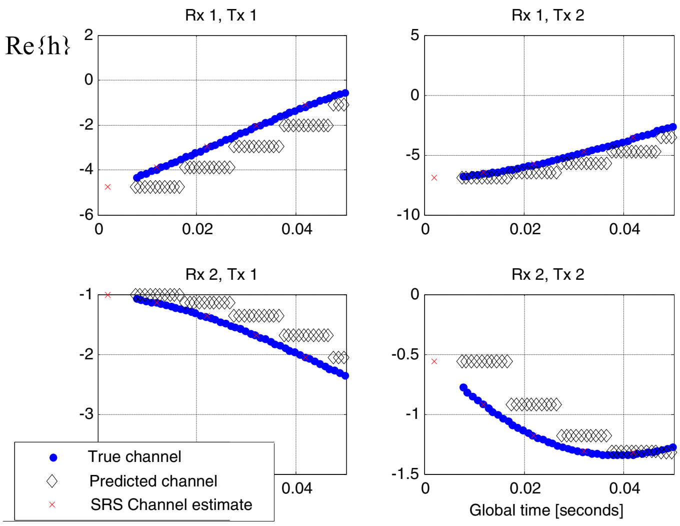

Figure 4. Real value of true channel realizations at DRS rate (blue dots), available channel realizations at SRS rate (red x-marks) and channel predictions at TTI rate (black diamonds) using delayed channel estimates only.

Performance results in terms of user throughput are illustrated in Figure 5 for several alternatives of using both ideal and delayed channel estimates. Here, the performance is illustrated when an ideal channel predictor is used (black stars), i.e. the true channel at the time instant of transmitting PUSCH is used both for PMI and MCS selection. When using delayed channel estimates for PMI selection, while keeping ideal channel estimates for MCS selection, the performance is almost unaffected (red triangles up). However, simulations of using ideal channel estimates for PMI selection and delayed channels for MCS selection indicates large performance degradations (blue circles). This indicates that it is mainly the MCS selection which suffers from delayed channel estimates and not the PMI selection. As a reference, the performance is also included with a PMI corresponding to a fixed rank 2 transmission (cyan triangle down), which is a unity matrix pre-coding [1]. Also, simulations are included with fixed PMI corresponding to rank 1 (cyan plus) and adaptive PMI for rank 1 (cyan x-marks).

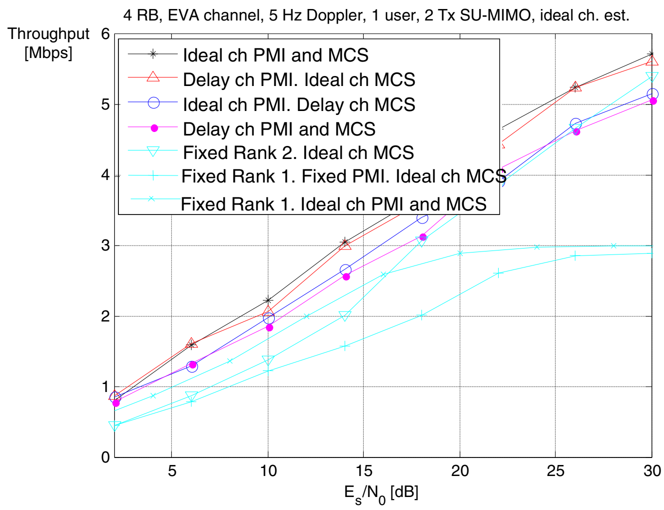

Figure 5. Performance of ideal and delayed channel estimates used in PMI and MCS selection

A Wiener-Hopf FIR predictor is illustrated with black diamonds in Figure 6. Here, the predicted channel is very close to the true channel after a few SRS channel estimates.

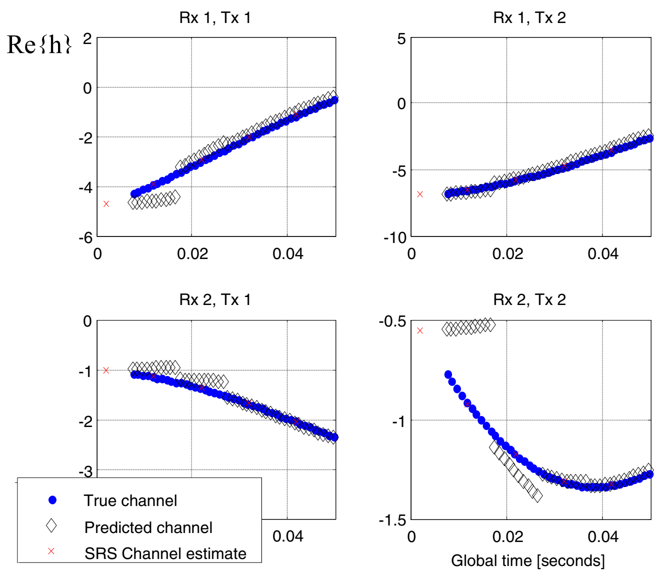

Figure 6. Real value of true channel (at TTI rate), available channel realizations (at SRS rate) and channel predictions (at TTI rate) using a Wiener-Hopf predictor.

Simulation results, in terms of user throughput, is given in Figure 7, when a Wiener-Hopf predictor is used (green x-marks), as described in section II.B. The performance of this predictor is close to using the ideal channel estimate (black dots) and up to 3 dB better than the simulation results with delayed channel for PMI and LA (as illustrated with magenta dots).

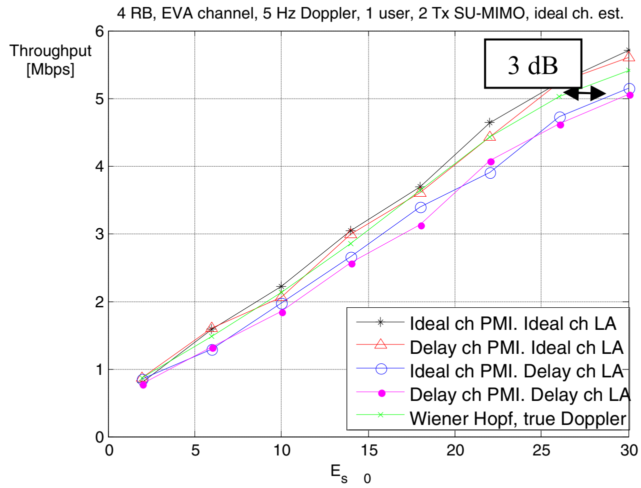

Figure 7. Performance of Wiener-Hopf predictor

IV. Conclusions

The performance of LTE uplink can be significantly improved by using a channel predictor in the link adaptation. Here it is more important to have a good channel predictor for MCS selection compared to PMI selection. This link adaptation is based on an expression for SINR which is derived for an MMSE based single tap channel model suitable for LTE uplink.

V. References

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