ON ACK/NACK MESSAGES DETECTION IN THE LTE PUCCH WITH MULTIPLE RECEIVE ANTENNAS

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ABSTRACT

In this paper, we study ACK/NACK messages detection in the LTE physical uplink control channel (PUCCH) with multiple receive antennas. The LTE PUCCH is typically characterized by high interference variability due to severe inter-user interferences and slot-level frequency hopping. We present detection methods applicable for the cases when the noise variances at the receiver are known and unknown. Noise here may comprise both thermal noise and interference. The proposed detection technique is based on the generalized likelihood-ratio test (GLRT) paradigm. Simulation results show that GLRT-based detector offers a significant gain over the training-based maximum-likelihood detector when the noise variances in two slots are different and unknown. For the case when the noise variances at the receiver are known, the GLRT-based detector has nearly the same performance as the training-based maximum-likelihood detector.

Index Terms— signal detection, GLRT technique, LTE, multiple antennas

1. INTRODUCTION

Long Term Evolution (LTE) is a broadband wireless technology standardized recently by the Third Generation Partnership Project (3GPP). The goal of LTE is to provide high data rate services with low latency. For an LTE system with 20 MHz bandwidth, the peak data rate can reach up to 326 Mbps for the downlink and 86 Mbps for the uplink by using multiple input multiple output (MIMO) technologies.

In order to guarantee that the packets can be delivered over the radio link with the required level of reliability and latency, LTE employs a two-layer retransmission mechanism to handle erroneous packets: a hybrid automatic-repeat-request (HARQ) protocol on the physical layer and a highly reliable selective repeat ARQ protocol on the radio link control (RLC) layer. The HARQ mechanism in LTE targets fast retransmission after each received transport block. Basically, most errors can be captured and corrected by the HARQ protocol. To satisfy services with high reliability requirement, an ARQ protocol on the RLC layer is used to correct the residual errors due to the failure of the HARQ mechanism on the physical layer. Hence, a two-layer retransmission mechanism provides a good trade-off between low latency and reliable packet delivery.

Since the ultimate residual error rate of HARQ is in the same order as the feedback error rate of the ACK/NACK message, the ACK/NACK message detector for the physical uplink control channel (PUCCH) is an important factor that influences the overall downlink performance. Improving the error performance of the ACK/NACK message detector in the LTE PUCCH is thus important. To this end, papers [1] and [2] have studied methods to enhance the performance of the ACK/NACK detector in the LTE PUCCH under the assumption that the channel state information (CSI) and noise variance at the receiver are known or estimated. Noise here may comprise both thermal noise and intra-cell/inter-cell interference. However, as pointed out in [3], it is a hard task to estimate accurately the CSI and noise variance due to high interference variability in the LTE PUCCH. This is especially true for cell-edge users who experience large path losses and high inter-cell interference [4]. Therefore, it is interesting to study signal detection method which does not need CSI and noise variance information. With these observations, [5] proposed a GLRT-based detector for signal detection with unknown CSI and unknown noise variance for a multiple-antenna diversity system under flat fading channel model. Paper [3] formulates a basic framework for ACK/NACK message detection in the frequency-selective LTE PUCCH with imperfect CSI and unknown noise variances at the receiver.

In this paper, we derive GLRT-based detector for ACK/NACK messages detection in the LTE PUCCH with multiple receive antennas where ACK/NACK messages are transmitted with format 1b. We derive GLRT-based detection metrics for the cases when the noise variances at the receiver are known and unknown. For comparison, we also derive detection metrics for the conventional training-based maximum-likelihood detectors. We show that remarkable performance gains can be achieved by using the GLRT-based detectors compared to the conventional training-based maximum-likelihood detector when the noise variances in the two slots are different and unknown. This result is supported by the fact shown in [6] that for different noise variances the two channels should be weighted accordingly.

2. SYSTEM MODEL

In this paper, we focus on the ACK/NACK message detection in the LTE PUCCH with transmission format 1b where two ACK/NACK bits (in case of two MIMO codewords downlink transmission) are transmitted in the two slots of a subframe. We assume that ACK/NACK messages are transmitted with one transmit antenna

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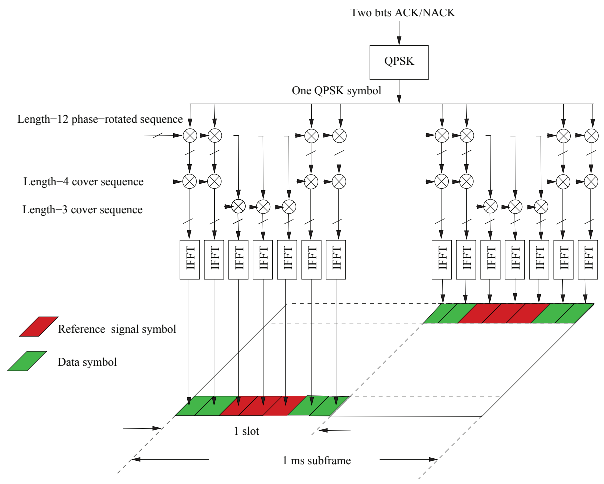

Fig. 1. Block diagram of PUCCH format 1b for normal CP (reproduced freely from [7]). The axes represent time and frequency, respectively.

(only a single power-amplifier is assumed to be available at the UE in LTE) and received at the eNodeB with M receive antennas. For illustration, we discuss the special case of two receive antennas. The generalization to M receive antennas is trivial. Fig. 1 shows the time-frequency structure of PUCCH format 1b with normal cyclic prefix (CP). As we can see from this figure, the PUCCH consists of two resource blocks located at the two edges of the total available cell bandwidth. Each resource block consists of $N = 12$ subcarriers in the frequency domain and $L = 7$ continuous OFDM symbols (1 slot) in the time domain. In each slot, 4 OFDM symbols (with indices 1, 2, 6, and 7) are used for the transmission of the QPSK-modulated ACK/NACK symbol s and the remaining 3 OFDM symbols are used for the transmission of the QPSK-modulated Pilot Symbols (PS) s_p. Resource blocks can be shared by multiple UEs using code division multiple access (CDMA) technology. This code spreading is done in two steps as shown in Fig. 1. Firstly, the ACK/NACK signals and PS are multiplied by a cell-specific length-12 cyclic shift sequence. Secondly, the ACK/NACK signals and PS are further code spread by length-4 and length-3 orthogonal cover sequences. Details about these sequences can be found in [7].

We assume that the channel gains are constant in one time slot, but change from one time slot to the next time slot. To simplify the notation, we also assume that the OFDM symbols which carry the ACK/NACK information are contiguous, i.e., there is no pilot symbol between them. At the receiver, after the fast Fourier transform (FFT) operation and undoing the effect of cyclic shift sequence and orthogonal cover sequences, the received PS and ACK/NACK signals at antenna $m = 1, 2$ in slot l over 12 subcarriers are given by

$$\mathbf{Y}_{m,l} = [\mathbf{Y}^p_{m,l} \ \mathbf{Y}^s_{m,l}] = \mathbf{h}_{m,l}[\mathbf{s}_p^T \ \mathbf{s}^T] + \mathbf{E}_{m,l}, \quad l = 1, 2, \quad (1)$$

where

- $\mathbf{Y}_{m,l}$ is an $N \times L$ matrix of received signals at receive antenna m.
- $\mathbf{Y}^p_{m,l}$ and $\mathbf{Y}^s_{m,l}$ are an $N \times 3$ matrix of received PS and an $N \times 4$ matrix of received ACK/NACK at receive antenna m, respectively.
- $\mathbf{h}_{m,l}$ is an $N \times 1$ vector of frequency domain channel gains from transmit antenna to receive antenna m.
- $\mathbf{s}_p \triangleq [s_p \ s_p \ s_p]^T$ and $\mathbf{s} \triangleq [s \ s \ s \ s]^T$ are vectors that contain the PS and modulated ACK/NACK symbols, respectively.
- $\mathbf{E}_{m,l}$ is an $N \times L$ matrix of additive noise with i.i.d. $\mathcal{CN}(0, \sigma^2_{m,l})$ elements. Note that the noise variances $\sigma^2_{m,l}$, $1 \leq \{m, l\} \leq 2$ are typically different. This is because the intra-cell/inter-cell interference at different antenna m and different time slot l in LTE PUCCH are different due to the fact these interference experience a different transmission path.

Assuming that $\mathbf{h}_{m,l}$ and $\sigma^2_{m,l}, 1 \leq \{m, l\} \leq 2$ are independent and perfectly known to the receiver, the maximum likelihood (ML) detector can be expressed

$$\hat{s}_{coh} = \arg\max_s \prod_{m=1}^{2}\prod_{l=1}^{2} p_{coh}(\mathbf{Y}^s_{m,l}|\mathbf{h}_{m,l}, \sigma^2_{m,l}, s), \quad (2)$$

where the conditional probability $p_{coh}(\mathbf{Y}^s_{m,l}|\mathbf{h}_{m,l}, \sigma^2_{m,l}, s)$ is given by

$$p_{coh}(\mathbf{Y}^s_{m,l}|\mathbf{h}_{m,l}, \sigma^2_{m,l}, s) = \frac{1}{(\pi\sigma^2_{m,l})^{4N}} \exp\left\{-\frac{\|\mathbf{Y}^s_{m,l} - \mathbf{h}_{m,l}\mathbf{s}^T\|^2}{\sigma^2_{m,l}}\right\}. \quad (3)$$

Here and henceforth $\|\cdot\|$ denotes the Frobenius matrix norm. After omitting constant factors and irrelevant terms in the metric calculation, the ML detector can be written as

$$\hat{s}_{coh} = \arg\max_s \operatorname{tr}\left(\sum_{m=1}^{2}\sum_{l=1}^{2} \frac{\operatorname{Re}\left\{\mathbf{Y}^s_{m,l}\mathbf{s}^*\mathbf{h}^\dagger_{m,l}\right\}}{\sigma^2_{m,l}}\right), \quad (4)$$

where $\mathbf{h}^\dagger_{m,l}$ denotes the Hermitian transpose of $\mathbf{h}_{m,l}$.

3. DETECTORS FOR UNKNOWN CHANNEL GAINS AND KNOWN NOISE VARIANCES

In practice, $\mathbf{h}_{m,l}$ and $\sigma^2_{m,l}, 1 \leq \{m, l\} \leq 2$ will be unknown or only partially known to the receiver. In this section we present three detectors for unknown $\mathbf{h}_{m,l}$ but known $\sigma^2_{m,l}$.

3.1. Optimal noncoherent detector

In this subsection, we consider the problem of detecting the transmitted symbol s without any prior estimate of the channel gains $\mathbf{h}_{m,l}, 1 \leq \{m, l\} \leq 2$. We assume that $\sigma^2_{m,l}$ and the distribution $p(\mathbf{h}_{m,l}), 1 \leq \{m, l\} \leq 2$ are perfectly known to the receiver. The optimal noncoherent detection problem can be written as

$$\begin{aligned}\hat{s}_{non} &= \arg\max_s \prod_{m=1}^{2}\prod_{l=1}^{2} p_{non}(\mathbf{Y}_{m,l}|\sigma^2_{m,l}, s) \\ &= \arg\max_s \prod_{m=1}^{2}\prod_{l=1}^{2} \mathrm{E}_{\mathbf{h}_{m,l}}\left[p(\mathbf{Y}_{m,l}|\mathbf{h}_{m,l}, \sigma^2_{m,l}, s)\right], \quad (5)\end{aligned}$$

where

$$p(\mathbf{Y}_{m,l}|\mathbf{h}_{m,l}, \sigma^2_{m,l}, s) = \frac{1}{(\pi\sigma^2_{m,l})^{LN}} \exp\left\{-\frac{\|\mathbf{Y}_{m,l} - \mathbf{h}_{m,l}\bar{\mathbf{s}}^T\|^2}{\sigma^2_{m,l}}\right\} \quad (6)$$

$$\mathrm{E}_{\mathbf{h}_{m,l}}\left[p(\mathbf{Y}_{m,l}|\mathbf{h}_{m,l},\sigma^2_{m,l},s)\right] = \frac{1}{(\pi\sigma^2_{m,l})^{LN}}\mathrm{E}_{\mathbf{h}_{m,l}}\left[\exp\left\{-\frac{\|\mathbf{Y}_{m,l}-\mathbf{h}_{m,l}\bar{\mathbf{s}}^T\|^2}{\sigma^2_{m,l}}\right\}\right]$$
$$= \frac{1}{(\pi\sigma^2_{m,l})^{LN}\det(\mathbf{R}_{hh}\mathbf{A}_{m,l})}\exp\left\{-\frac{\mathrm{tr}\left(\mathbf{Y}_{m,l}\mathbf{Y}^\dagger_{m,l}\right)}{\sigma^2_{m,l}}+\frac{\bar{\mathbf{s}}^T\mathbf{Y}^\dagger_{m,l}\mathbf{A}^{-1}_{m,l}\mathbf{Y}_{m,l}\bar{\mathbf{s}}^*}{\sigma^4_{m,l}}\right\}. \quad (7)$$

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and $\bar{\mathbf{s}} \triangleq [\mathbf{s}_p^T\ \mathbf{s}^T]^T$ is an $L\times 1$ vector of transmitted reference signals and ACK/NACK signals. Consider the system model in (1), and suppose that $\mathbf{h}_{m,l} \sim \mathcal{CN}(\mathbf{0},\mathbf{R}_{hh})$, where $\mathbf{R}_{hh}$ is the covariance matrix of the channel gains on all $N = 12$ subcarriers, i.e.,

$$\mathbf{R}_{hh} = \mathrm{E}[\mathbf{h}_{m,l}\mathbf{h}^\dagger_{m,l}]. \quad (7)$$

We further define $\mathbf{A}_{m,l} \triangleq \frac{\|\bar{\mathbf{s}}\|^2}{\sigma^2_{m,l}}\mathbf{I} + \mathbf{R}^{-1}_{hh}, 1 \le \{m,l\} \le 2$ and assume that $\mathbf{h}_{m,l}, 1 \le \{m,l\} \le 2$ are independent. With these assumptions, we can obtain $\mathrm{E}_{\mathbf{h}_{m,l}}\left[p(\mathbf{Y}_{m,l}|\mathbf{h}_{m,l},\sigma^2_{m,l},s)\right]$ as shown in equation (7) on the top of the page. Insertion of (7) in (5) and dropping constant terms gives the optimal noncoherent detector

$$\hat{s}_{non} = \arg\max_s \prod_{m=1}^{2}\prod_{l=1}^{2}\frac{\exp\left\{\frac{\bar{\mathbf{s}}^T\mathbf{Y}^\dagger_{m,l}\mathbf{A}^{-1}_{m,l}\mathbf{Y}_{m,l}\bar{\mathbf{s}}^*}{\sigma^4_{m,l}}\right\}}{\det(\mathbf{R}_{hh}\mathbf{A}_{m,l})}. \quad (8)$$

3.2. Mismatched maximum-likelihood (MML) detector

A commonly used receiver in practice is to first estimate the channel gains $\mathbf{h}_{m,l}$ from the PS, and then insert the estimate into the coherent metric (4) as if the channel were perfectly known. There are several possible mismatched receivers depending on the type of channel estimation algorithm used. If least-squares estimation is used, the estimated channel gain can be expressed as

$$\begin{aligned}\hat{\mathbf{h}}_{m,l} &= \arg\min_{\mathbf{h}_{m,l}}\|\mathbf{Y}^p_{m,l}-\mathbf{h}_{m,l}\mathbf{s}_p^T\|^2 \\ &= \mathbf{Y}^p_{m,l}\mathbf{s}_p^*(\mathbf{s}_p^T\mathbf{s}_p^*)^{-1} = \frac{\mathbf{Y}^p_{m,l}\mathbf{s}_p^*}{\|\mathbf{s}_p\|^2}. \end{aligned} \quad (9)$$

By using (4), we get the following MML detector

$$\hat{s}_{MML} = \arg\max_s \mathrm{tr}\left(\sum_{m=1}^{2}\sum_{l=1}^{2}\frac{\mathrm{Re}\left\{\mathbf{Y}^s_{m,l}\mathbf{s}^*\hat{\mathbf{h}}^\dagger_{m,l}\right\}}{\sigma^2_{m,l}}\right). \quad (10)$$

3.3. GLRT detector

The optimal noncoherent detector is derived under the assumption that the exact probability density function (PDF) $p(\mathbf{h}_{m,l}), 1 \le \{m,l\} \le 2$ is perfectly known to the receiver. This limits the usefulness of the optimal noncoherent detector since the exact PDF $p(\mathbf{h}_{m,l}), 1 \le \{m,l\} \le 2$ will never be known in practice. Furthermore, the detector (8) is optimal only when $\mathbf{h}_{m,l}$ and $\mathbf{E}_{m,l}$ have the assumed PDF which is not necessarily true for LTE PUCCH. The problem with the MML detector is that its performance is sensitive to noise variances and will significantly degrade when the noise variances at the receiver is large. Therefore, it is important to design a new detector which is robust to the channel uncertainty.

Here we derive a detector based on the GLRT. The basic idea of GLRT is to first obtain the maximum likelihood estimate (MLE) of the unknown parameters by maximizing the likelihood functions, and then form the detection metric by substituting the unknown parameters in the likelihood functions with the MLE. For the system considered here, the maximization of the likelihood function with respect to $\mathbf{h}_{m,l}$ yields the equation

$$\mathbf{h}_{m,l}\bar{\mathbf{s}}^T\bar{\mathbf{s}}^* - \mathbf{Y}_{m,l}\bar{\mathbf{s}}^* = 0. \quad (11)$$

The MLE of $\mathbf{h}_{m,l}$ that maximizes the probability density function (6) can now be obtained as

$$\mathbf{h}_{m,l} = \mathbf{Y}_{m,l}\bar{\mathbf{s}}^*(\bar{\mathbf{s}}^T\bar{\mathbf{s}}^*)^{-1},\ \ 1 \le \{m,l\} \le 2. \quad (12)$$

Insertion of (12) into (6) yields

$$p(\mathbf{Y}_{m,l}|\sigma^2_{m,l},s) = \frac{1}{(\pi\sigma^2_{m,l})^{LN}}\times \exp\left\{-\frac{\mathrm{tr}\left(\mathbf{Y}_{m,l}\mathbf{Y}^\dagger_{m,l}-\mathbf{Y}_{m,l}\bar{\mathbf{s}}^*\bar{\mathbf{s}}^T\mathbf{Y}^\dagger_{m,l}(\bar{\mathbf{s}}^T\bar{\mathbf{s}}^*)^{-1}\right)}{\sigma^2_{m,l}}\right\}. \quad (13)$$

Hence, the GLRT detector will have the following form

$$\hat{s}_{GLRT} = \arg\max_s \prod_{m=1}^{2}\prod_{l=1}^{2}p(\mathbf{Y}_{m,l}|\sigma^2_{m,l},s). \quad (14)$$

Omitting the constant factor and irrelevant terms in the metric calculation, the detector can finally be rewritten as

$$\hat{s}_{GLRT} = \arg\max_s \mathrm{tr}\left(\sum_{m=1}^{2}\sum_{l=1}^{2}\frac{\mathbf{Y}_{m,l}\bar{\mathbf{s}}^*\bar{\mathbf{s}}^T\mathbf{Y}^\dagger_{m,l}(\bar{\mathbf{s}}^T\bar{\mathbf{s}}^*)^{-1}}{\sigma^2_{m,l}}\right). \quad (15)$$

After some mathematical operations and omitting the constant factor, we can show that the GLRT-based metric in (15) is the same as the training-based metric in (10). In other words, the MML detector and the GLRT detector are equivalent under the assumption of known $\sigma^2_{m,l}$. This can also be clearly seen from the simulation results presented in Section V.

4. DETECTORS FOR UNKNOWN CHANNEL GAINS AND UNKNOWN NOISE VARIANCES

We now proceed to derive detectors for unknown $\mathbf{h}_{m,l}$ and $\sigma^2_{m,l}$. In principle, all three detectors described in Section III can be extended to this case. However, to marginalize the conditional density of noncoherent detector in (7) over a prior $p(\sigma^2_{m,l})$ results in a computationally very intractable problem. Hence, we only present MML and GLRT detectors in this section.

4.1. Mismatched maximum-likelihood (MML) detector

MML detector will first estimate $\sigma^2_{m,l}$ form the PS. Then the estimated $\sigma^2_{m,l}$ will be used for ACK/NACK message detection. With the estimated channel gain $\hat{\mathbf{h}}_{m,l}$ in (9), the maximum-likelihood (ML) estimate of the noise variance can be expressed as

$$\hat{\sigma}^2_{m,l} = \frac{1}{2N}\|\mathbf{Y}^p_{m,l} - \hat{\mathbf{h}}_{m,l}\mathbf{s}^T_p\|^2. \quad (16)$$

Then, using (10), we get the following MML detector

$$\hat{s}_{MML} = \arg\max_s \operatorname{tr}\left(\sum_{m=1}^{2}\sum_{l=1}^{2}\frac{\operatorname{Re}\left\{\mathbf{Y}^s_{m,l}\mathbf{s}^*\hat{\mathbf{h}}^\dagger_{m,l}\right\}}{\hat{\sigma}^2_{m,l}}\right). \quad (17)$$

4.2. GLRT detector

We next consider the GLRT detector where the explicit estimation of $\sigma^2_{m,l}$ is not needed. With the GLRT paradigm, we will form the detection metric by substituting the unknown parameters $\sigma^2_{m,l}$ in the metric functions (15) with the MLE of $\sigma^2_{m,l}$. Using (13), the maximization of the probability density function $p(\mathbf{Y}_{m,l}|\sigma^2_{m,l}, s)$ with respect to $\sigma^2_{m,l}$ yields the equation

$$\frac{\operatorname{tr}\left(\mathbf{Y}_{m,l}\mathbf{Y}^\dagger_{m,l} - \mathbf{Y}_{m,l}\bar{\mathbf{s}}^*\bar{\mathbf{s}}^T\mathbf{Y}^\dagger_{m,l}(\bar{\mathbf{s}}^T\bar{\mathbf{s}}^*)^{-1}\right)}{\sigma^4_{m,l}} - \frac{LN}{\sigma^2_{m,l}} = 0. \quad (18)$$

Hence, the MLE of $\sigma^2_{m,l}$ that maximizes $p(\mathbf{Y}_{m,l}, |\sigma^2_{m,l}, s)$ can be obtained as

$$\sigma^2_{m,l} = \frac{\operatorname{tr}\left(\mathbf{Y}_{m,l}\mathbf{Y}^\dagger_{m,l} - \mathbf{Y}_{m,l}\bar{\mathbf{s}}^*\bar{\mathbf{s}}^T\mathbf{Y}^\dagger_{m,l}(\bar{\mathbf{s}}^T\bar{\mathbf{s}}^*)^{-1}\right)}{LN}. \quad (19)$$

Insertion of (19) into (13) yields

$$p(\mathbf{Y}_{m,l}|s) = \frac{(LN)^{LN}\exp\{-LN\}}{\left[\pi \operatorname{tr}\left(\mathbf{Y}_{m,l}\mathbf{Y}^\dagger_{m,l} - \mathbf{Y}_{m,l}\bar{\mathbf{s}}^*\bar{\mathbf{s}}^T\mathbf{Y}^\dagger_{m,l}(\bar{\mathbf{s}}^T\bar{\mathbf{s}}^*)^{-1}\right)\right]^{LN}}. \quad (20)$$

The GLRT detector will have the following form

$$\hat{s}_{GLRT} = \arg\max_s \prod_{m=1}^{2}\prod_{l=1}^{2} p(\mathbf{Y}_{m,l}|s). \quad (21)$$

After taking the logarithm of the metric (21) and dropping irrelevant constants, we get the following GLRT detector

$$\hat{s}_{GLRT} = \arg\min_s \sum_{m=1}^{2}\sum_{l=1}^{2} \log\left\{\operatorname{tr}\left(\mathbf{Y}_{m,l}\mathbf{Y}^\dagger_{m,l} - \mathbf{Y}_{m,l}\bar{\mathbf{s}}^*\bar{\mathbf{s}}^T\mathbf{Y}^\dagger_{m,l}(\bar{\mathbf{s}}^T\bar{\mathbf{s}}^*)^{-1}\right)\right\}. \quad (22)$$

5. NUMERICAL RESULTS

In this section, we present Monte Carlo simulation results to illustrate the performances of the proposed detectors. We consider a LTE PUCCH system with one transmit antenna and two receive antennas. The system consists of 300 subcarriers with 15 KHz subcarrier separation. The ACK/NACK messages are transmitted in format 1b.

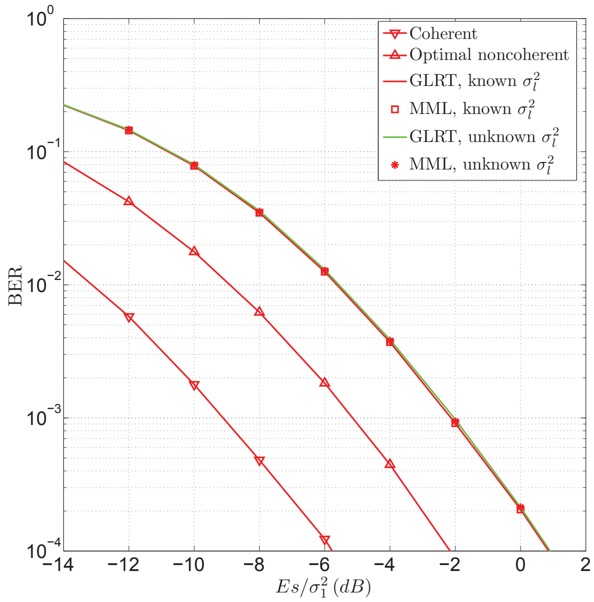

Fig. 2. Performance comparison of all detectors for the case $\sigma_1^2 = \sigma_2^2$.

In our simulation, we adopt a Rayleigh fading channel model that follows the 3GPP Extended Vehicular A power delay profile with maximum Doppler frequency $f_{\max} = 20$ Hz. The channel coefficients are assumed to be constant over the duration of one slot interval, but vary from slot to slot. The temporal autocorrelation of the complex channel gain between slots is described by the autocorrelation functions $R(\tau) = J_0(2\pi f_{\max}\tau)$, where $J_0(x)$ is the zeroth order Bessel function of the first kind. We also assume that the channel gains between the two receive antennas are independent and $\sigma^2_{1,l} = \sigma^2_{2,l} = \sigma^2_l, l = 1, 2$. The notation E_s/σ_1 refers to the mean received SNR.

Fig. 2 illustrates the bit-error rate (BER) performance of the MML and GLRT detectors with known and unknown noise variances when we set $\sigma_1^2 = \sigma_2^2$. The BER performances of the coherent detectors and optimal noncoherent detector are also included for reference. We can see that the GLRT detector has nearly the same performance as MML detector for both known and unknown noise variances cases. The advantage of the GLRT detector is that it does not need any *a priori* assumptions on the statistical distributions of the channel coefficients or the noise variance. The simulation results also verify the fact that the MML detector and the GLRT detector are equivalent under the assumption of known σ_l^2.

Next, we look at the BER performance when $\sigma_1^2 \neq \sigma_2^2$. Fig. 3 shows the BER performance when we set $\sigma_2^2/\sigma_1^2 = 10$ dB. It can be observed that the GLRT detector yields an improvement in SNR of about 2 dB over the MML detector at BER of 10^{-2} if the noise variances are unknown to the receiver. Fig. 4 shows the same result when we set $\sigma_2^2/\sigma_1^2 = 20$ dB. As we can see from the figure, the performance improvement increases to 6.5 dB for this case. These results demonstrate that the GLRT detector with unknown noise variances provides a significant gain compared to its training-based counterpart when $\sigma_1^2 \neq \sigma_2^2$. It can also be observed that the MML detector and the GLRT detector have the same performance if the noise variances are known to the receiver. Furthermore, it can

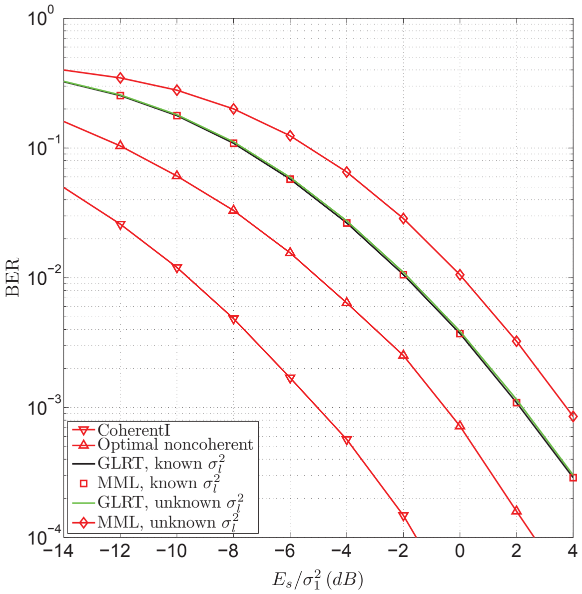

Fig. 3. Performance comparison of all detectors for the case $\sigma_2^2/\sigma_1^2 = 10$ dB.

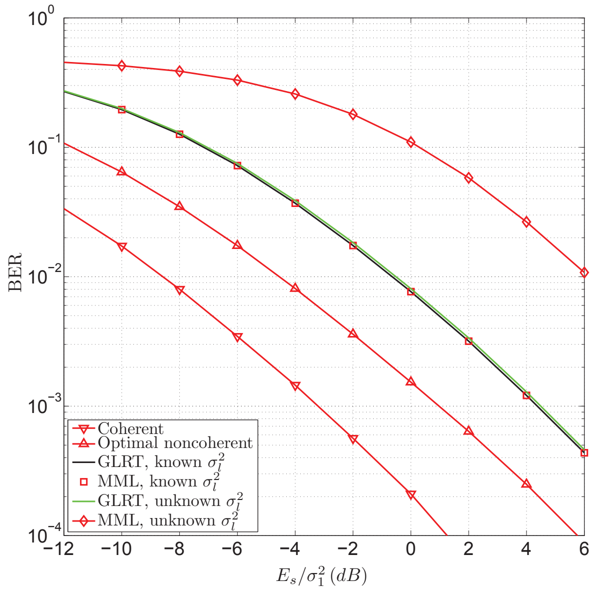

Fig. 4. Performance comparison of all detectors for the case $\sigma_2^2/\sigma_1^2 = 20$ dB.

be found that the GLRT detector with unknown noise variances has nearly the same BER performance as the GLRT detector with known noise variances. In other words, the GLRT detector with unknown noise variance can perform as well as a training-based detector with known noise variances. Note that these conclusions are coincide with those drawn in [3] for the GLRT detector for LTE PUCCH with format 1a and single receive antenna.

6. CONCLUSIONS

We have developed GLRT detectors for ACK/NACK message detection in the LTE PUCCH with multiple receive antennas. Simulation results show that the GLRT detector offers a significant gain over the MML detector when the noise variances in two slots are different and unknown. For all the other cases, GLRT detector has nearly the same BER performance as MML detector. This shows that GLRT detector is a robust detector for the LTE PUCCH with multiple receive antennas when ACK/NACK messages are transmitted with format 1b. For future work, it may be of some interest to extend the GLRT detector presented here to the case when ACK/NACK messages are transmitted with format 2a where ACK/NACK messages and channel quality indication are transmitted together.

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