

**Agenda item:** 9.7.2  
**Source:** Renesas Mobile Europe Ltd  
**Title:** Receiver structure feasibility for LTE Rel-12  
**Document for:** Discussion

---

## 1 Introduction

During RAN#59 plenary it has been agreed to start a RAN1/4 Rel-12 study item on network-assisted interference cancellation and suppression for LTE UE [1]. In this contribution we address the following objective of the study item

- *Analyze complexity and feasibility of basic receiver structures*
  - *Receiver structures based on linear MMSE IRC, successive interference cancellation, and maximal likelihood detection are considered as a starting point for reference IS/IC receivers*

---

## 2 Scope of UE receiver enhancements in Rel-12

In general, our view is that UE receiver evolution in terms of interference mitigation capabilities consists of optional enhancements on top of previous releases. A first step towards linear interference suppression was made in Rel-11 with LMMSE-IRC reference receiver. The next natural step is further harvesting of the network assisted benefits of LMMSE-IRC, which could be done with limited specification impact, if any. Further on the evolution of advanced receivers would generally be the introduction of interference cancellation – i.e. non-linear interference mitigation – on top of interference suppression. The justification lies in the amount of side information as well as receiver complexity that both increase when applying interference cancellation instead of interference suppression. Interference suppression typically exploits statistics on the interference whereas specific side information – e.g. modulation or modulation and coding – is in general required by the cancellation algorithms.

The NAICS study targets several types of IC/IS in the form of inter-stream, inter-user and inter-cell. These forms of interference have different needs in terms of network assistance. For example, inter-stream interference, understood here as SU-MIMO, can be readily performed as the needed information is implicit at the UE. From this perspective RAN4 would need to assess the gains of more advanced demodulation and decoding structures. The cases of inter-user and inter-cell IC/IS need obviously more elaboration. The interference structure availability at the receiver is an important study point. In addition, to some extent a decoupled problem is the complexity of the IC/IS loop of the candidate decoders in face of number of desired and interfering streams. Other factors like the potential introduction of 256 QAM in Rel-12 should be carefully taken into account when performing the complexity assessment.

**Proposal 1:** *Complexity assessment of the candidate decoders should consider factors like interference structure availability, number of desired and interfering streams as well as the potential introduction of 256 QAM.*

---

## 3 System Model

To provide further insights on different candidate MIMO detectors for Rel-12, let us firstly describe the used system model. For notational simplicity, a sub-carrier as well as physical resource block indices are omitted for the rest of this presentation. Let us consider a multi-user (MU) multiple-input-multiple output (MIMO) downlink (DL) transmission in a multi-cell network which consists of  $|\mathcal{B}|$  cells, where  $\mathcal{B}$  defines the set of base stations (BS)s and  $|\cdot|$  indicates the cardinality of a set, hence the number of BSs. Each base station is equipped with  $N_T$  transmit antennae and serves  $|U_n|$  user equipments (UE)s. It is worth noting that by using linear precoding techniques the total number of data streams served by each BS is upper bounded by  $N_T$  transmit antennas. Here, the set  $U_n$  defines the set of simultaneously served UEs on same time and frequency resources associated with the  $n^{\text{th}}$  BS. Each UE can be equipped with  $N_R$  receive antennae and is able to receive simultaneously up to  $N_R$  data streams. For the  $k^{\text{th}}$  UE served by the  $n^{\text{th}}$  BS, the received

DL space-frequency signal  $\mathbf{r}_{n_k} \in \mathbb{C}^{N_R}$  after cyclic prefix removal and fast Fourier transformation (FFT) can be expressed as:

$$\mathbf{r}_{n_k} = \mathbf{H}_{n_k,n} \mathbf{t}_{n_k,d} b_{n_k,d} + \mathbf{H}_{n_k,n} \sum_{s \in \mathcal{S}_{n_k,d}} \mathbf{t}_{n_k,s} b_{n_k,d} + \mathbf{H}_{n_k,n} \sum_{j \in \mathcal{U}_{n_k}} \sum_{l \in \mathcal{S}_{n_j}} \mathbf{t}_{n_j,l} b_{n_j,l} + \sum_{m \in \mathcal{B} \setminus n} \mathbf{H}_{n_k,m} \sum_{i \in \mathcal{U}_m} \sum_{v \in \mathcal{S}_{n_i}} \mathbf{t}_{m_i,v} b_{m_i,v} + \mathbf{n}_{n_k} \quad (1)$$

where  $\mathbf{H}_{n_k,n} \in \mathbb{C}^{N_R \times N_T}$  represents a frequency domain channel matrix which consists of small-scale and large-scale fading components, associated with the link between the  $k^{\text{th}}$  UE and the  $n^{\text{th}}$  BS. The vector  $\mathbf{t}_{n_k,d} \in \mathbb{C}^{N_T}$  denotes precoder for the  $d^{\text{th}}$  data stream of the  $k^{\text{th}}$  UE associated with the  $n^{\text{th}}$  serving BS and  $\mathcal{S}_{n_k, nk}$  describes the set of data streams for the  $k^{\text{th}}$  UE associated with the  $n^{\text{th}}$  BS. The scalar  $b_{n_k,d}$  represent modulated data symbol for the  $d^{\text{th}}$  data stream of the  $k^{\text{th}}$  UE. The vector  $\mathbf{n}_{n_k} \sim \mathcal{CN}(\mathbf{0}, N_0 \mathbf{I}) \in \mathbb{C}^{N_R}$  represents additive white Gaussian noise at a receiver where  $N_0$  is the variance of the noise. It is worth noting that the first term in (1) represents a desired signal, the second inter-stream-interference, the third intra-cell-interference and the fourth inter-cell-interference components, respectively.

---

## 4 Candidate Detector Structures for LTE Rel-12

In this section, a generic description of the Rel-12 candidate detectors is provided. The SID text identifies several different detector options, namely, interference rejection combining (IRC), successive interference cancellation (SIC) and maximum likelihood (ML). All of them can be categorized to belong into either to the group of linear or non-linear detectors. In the following, interference-aware linear and non-linear detectors for Rel-12 LTE are, discussed.

In general, optimal joint detection and decoding schemes for minimizing the bit error rate and the sequence error rate are non-linear and are based on maximum-likelihood/maximum a posteriori (ML)/(MAP) estimation. Since the computational complexity of the optimal joint detection and decoding is prohibitive, a standard approach to reduce computational complexity of the receivers to split the joint problem into two separate problems, namely, detection and decoding. In the LTE, a turbo decoder resolves the decoding problem, and a MIMO detector recovers the desired transmitted signal from a received signal in the presence of interference, i.e. intra-cell-interference, inter-cell-interference and noise, components.

Since the interference structure knowledge can further differentiate the candidate detector structures, in the following the main assumption is that interference-awareness (IA) refers to a detector capability to exploit the structure of interfering signals in a detection process.

### 4.1 Interference-Aware Linear Detectors

In this subsection, IA linear detectors for LTE Rel-12 are considered. More specifically, the linear detectors such as linear MMSE-IRC and widely linear-MMSE-IRC are described.

#### 4.1.1 LMMSE-IRC

This subsection focuses on a well-known IRC detector based on linear minimum mean square error (LMMSE) criterion. In Rel-11, the performance requirements for the LMMSE-IRC detector have been specified [4]. Hence, the Rel-11 based LMMSE-IRC detector is the baseline detector in this study.

The major target of LMMSE-IRC detector is to suppress inter-layer, intra-/and inter-cell-interference signal components while detecting a desired signal. Mathematically, by using (1), the estimate of transmitted desired symbol of the  $d^{\text{th}}$  data stream  $\hat{b}_{n_k,d}$  can be expressed as

$$\hat{b}_{n_k,d} = \mathbf{w}_{n_k,d}^{\text{IRC}^H} \mathbf{r}_{n_k} \quad (2)$$

where the coefficients of the LMMSE-IRC detector  $\mathbf{w}_{n_k,d}^{\text{IRC}} \in \mathbb{C}^{N_R}$  for the  $k^{\text{th}}$  user associated with the  $n^{\text{th}}$  serving BS and the  $d^{\text{th}}$  stream are computed as

$$\mathbf{w}_{n_k,d}^{\text{IRC}} = \boldsymbol{\Sigma}_{n_k}^{\text{IRC}^{-1}} \mathbf{H}_{n_k,n} \mathbf{t}_{n_k,d} \bar{\sigma}_{n_k,d}^2 \quad (3)$$

where  $\bar{\sigma}_{n_k,d}^2$  represents the power of a modulation symbol, and  $\boldsymbol{\Sigma}_{n_k}^{\text{IRC}} \in \mathbb{C}^{N_R \times N_R}$  is an estimate of interference covariance matrix for the LMMSE-IRC detector including the contribution of a desired and interfering signal components, respectively. Here, we rely on Rel-11 based covariance matrix estimation methods, i.e. based on common reference signal (CRS) and demodulation reference signal (DM-RS), which are described in [4]. After the LMMSE-IRC detection stage, the estimated transmitted symbols are converted to a bit-level information, e.g. log-likelihood-ratios (LLR)s, to be further processed by a turbo decoder.

#### 4.1.2 Widely Linear MMSE-IRC (WMMSE-IRC)

In this subsection, a WMMSE-IRC detector is briefly described. The basic idea of widely linear filtering is to apply two complex valued filters to filter the received signal and its complex conjugate counterpart, respectively. An alternative way to describe the WMMSE-IRC detector, more illustrative, is to rewrite the signal model by using real valued signals, i.e. splitting the real and imaginary components in augmented vectors and matrices. In other words, the model introduced in (1) can be re-written as:

$$\mathbf{r}_{n_k}^A = \mathbf{H}_{n_k,n,d}^A \mathbf{b}_{n_k,d}^A + \mathbf{n}_{n_k}^A \quad (4)$$

where

$$\mathbf{r}_{n_k}^A = \begin{bmatrix} \Re(\mathbf{r}_{n_k}) \\ \Im(\mathbf{r}_{n_k}) \end{bmatrix} \in \mathbb{R}^{2N_R} \quad (5)$$

$$\mathbf{H}_{n_k,n,d}^A = \begin{bmatrix} \Re(\mathbf{H}_{n_k,n} \mathbf{t}_{n_k,d}) - \Im(\mathbf{H}_{n_k,n} \mathbf{t}_{n_k,d}) \\ \Im(\mathbf{H}_{n_k,n} \mathbf{t}_{n_k,d}) \Re(\mathbf{H}_{n_k,n} \mathbf{t}_{n_k,d}) \end{bmatrix} \in \mathbb{R}^{2N_R \times 2} \quad (6)$$

$$\mathbf{b}_{n_k,d}^A = \begin{bmatrix} \Re(b_{n_k,d}) \\ \Im(b_{n_k,d}) \end{bmatrix} \in \mathbb{R}^2 \quad (7)$$

$$\mathbf{n}_{n_k}^A = \begin{bmatrix} \Re(\tilde{\mathbf{n}}_{n_k}) \\ \Im(\tilde{\mathbf{n}}_{n_k}) \end{bmatrix} \in \mathbb{R}^{2N_R} \quad (8)$$

$$\tilde{\mathbf{n}}_{n_k} = \mathbf{H}_{n_k,n} \sum_{s \in \mathcal{S}_{n_k,d}} \mathbf{t}_{n_k,s} b_{n_k,d} + \mathbf{H}_{n_k,n} \sum_{j \in \mathcal{U}_{n_k}} \sum_{l \in \mathcal{S}_{n_j}} \mathbf{t}_{n_j,l} b_{n_j,l} + \sum_{m \in \mathcal{B} \setminus n} \mathbf{H}_{n_k,m} \sum_{i \in \mathcal{U}_m} \sum_{v \in \mathcal{S}_{n_i}} \mathbf{t}_{m_i,v} b_{m_i,v} + \mathbf{n}_{n_k} \mathbb{C}^{N_R} \quad (9)$$

where operators,  $\Re(\cdot)$  and  $\Im(\cdot)$  take the real and imaginary parts of their arguments, respectively. The output of the WMMSE-IRC detector is given by

$$\begin{bmatrix} \hat{b}_{n_k,d}^{\text{re}} \\ \hat{b}_{n_k,d}^{\text{im}} \end{bmatrix} = \mathbf{W}_{A n_k,d}^T \mathbf{r}_{n_k}^A \in \mathbb{R}^2 \quad (10)$$

where, scalars  $\hat{b}_{n_k,d}^{\text{re}}$ ,  $\hat{b}_{n_k,d}^{\text{im}}$  are the in-phase and quadrature-phase estimates of the transmitted modulation symbol, respectively. Finally, the coefficients of a WMMSE-IRC filter  $\mathbf{W}_{A n_k,d} \in \mathbb{R}^{2N_R \times 2}$  can be computed as

$$\mathbf{W}_{A n_k,d} = \boldsymbol{\Sigma}_{n_k}^{\text{IRC,A}^{-1}} \mathbf{H}_{n_k,n,d}^A \mathbf{C}_{bb} \quad (11)$$

In the above equation, the covariance of the received signal in the augmented signal model equals

$$\boldsymbol{\Sigma}_{n_k}^{\text{IRC,A}} = \mathbf{H}_{n_k,n,d}^A \mathbf{C}_{bb} \mathbf{H}_{n_k,n,d}^{A T} + \text{E} \left[ \mathbf{n}_{n_k}^A \mathbf{n}_{n_k}^{A T} \right] \in \mathbb{R}^{2N_R \times 2N_R} \quad (12)$$

where  $\mathbf{C}_{bb} = \text{E} \left[ \mathbf{b}_{n_k,d}^A \mathbf{b}_{n_k,d}^{A T} \right] \in \mathbb{R}^{2 \times 2}$  equals the covariance of transmitted symbol constellation in the IQ domain. For complex valued modulations, the matrix  $\mathbf{C}_{bb}$  is a scaled identity matrix but for real valued modulation the autocovariance of imaginary part equals zero. In the same way, the modulation method is visible in the interference covariance. Although the WMMSE-IRC estimator estimates a vector of real values, similar symbol-to-bit mapping approach can be used as in the conventional LMMSE-IRC because of the used QAM constellation.

In general, the major benefit for the usage of widely linear filtering is to increase the detector's degrees of freedom from  $N_R$  to  $2N_R$ . Particularly, this holds strictly if both desired and interfering signals employ a real-valued modulation scheme. As a consequence, the interference suppression capability of linear interference-aware detector can be significantly enhanced, from  $N_R-1$  to  $2N_R-1$ , leading to an improved performance in interference limited scenarios. Such interference suppression capability is demonstrated in an accompanying paper [3].

## 4.2 Interference-Aware Non-linear Detectors

In this subsection, interference-aware non-linear detectors are discussed. Particularly, we focus on the LMMSE-SIC and the maximum-likelihood (ML) criterion based joint detection techniques.

### 4.2.1 LMMSE based Successive Interference Cancellation

In this subsection, a modulation symbol based and a codeword based LMMSE-SIC detection approaches are considered. The basic idea of both LMMSE-SIC based detectors is to detect intended and interfering signals sequentially by subtracting detected signals from the received signal. Primary difference between the symbol and the codeword based schemes is whether the subtracted signal is reconstructed based the output of the LMMSE filter, i.e. modulation symbol based, or a turbo decoder, i.e. codeword based, respectively. As a result, the symbol based SIC may perform interference cancellation on a modulation symbol basis whereas the codeword based on a codeword basis, respectively.

#### 4.2.1.1 Codeword based LMMSE-SIC

Let us firstly introduce a codeword based LMMSE-SIC. As mentioned earlier, the basic idea of the codeword based SIC detector is to detect intended and interfering signals sequentially by exploiting the output of a turbo decoder by subtracting the decoded signals from the received signal. Typically, a successive filtering and cancellation process is performed for dominating signal components, i.e. interfering/desired. For a notational simplicity, the indices related to the successive filtering and cancellation stages are omitted from the following consideration. At the beginning of each successive stage, a modified received signal  $\check{\mathbf{r}}_{n_k}^{\text{cw-sic}} \in \mathbb{C}^{N_R}$  is filtered by a LMMSE filter to suppress interference as well as obtain an estimate of the strongest signal (either desired or interference). It is worth noting that at the beginning of a successive process, the modified received signal is identical with the actual received signal given in (1). The output of the LMMSE filter can be written as

$$\hat{\mathbf{b}}_{x_q,l} = \mathbf{w}_{n_k,d}^{\text{cw-sicH}} \mathbf{r}_{n_k,x_q,l}^{\check{\mathbf{r}}_{n_k}^{\text{cw-sic}}} \quad (13)$$

where  $\mathbf{w}_{n_k,d}^{\text{cw-sic}} \in \mathbb{C}^{N_R}$  determines the coefficients of an LMMSE filter for the  $k^{\text{th}}$  UE associated with the  $n^{\text{th}}$  BS for estimating a transmitted signal from the  $q^{\text{th}}$  UE associated with the  $x^{\text{th}}$  BS and the  $l^{\text{th}}$  data stream. By using (13), the LMMSE filter coefficients  $\mathbf{w}_{n_k,x_q,l}^{\text{H}} \in \mathbb{C}^{N_R}$  can be rewritten for the LMMSE-SIC detector as

$$\mathbf{w}_{n_k,d}^{\text{cw-sic}} \mathbf{r}_{n_k,x_q,l} = \boldsymbol{\Sigma}_{n_k}^{\text{cw-sic}^{-1}} \mathbf{H}_{n_k,x} \mathbf{t}_{x_q,l} \bar{\sigma}_{x_q,l}^2, \forall x \in \mathcal{B}^{\text{dom}}, \forall q \in \mathcal{U}_x^{\text{dom}}, \forall l \in \mathcal{S}_q^{\text{dom}} \quad (14)$$

As can be noted, the filter coefficients need to be computed for all combinations defined by the sets  $\mathcal{B}^{\text{dom}}$ ,  $\mathcal{U}_x^{\text{dom}}$  and  $\mathcal{S}_q^{\text{dom}}$  associated with indices to dominant interferer BSs, interferer UEs, interferer streams, respectively. Here, aforementioned sets are assumed to predefine before the successive detection process is initiated. To obtain the estimate of interference covariance matrix, widely known interference covariance estimation methods shown in [4] can be utilized. Additionally, it is worth noting that the estimate of the interference covariance matrix for the codeword based SIC scheme,  $\boldsymbol{\Sigma}_{n_k}^{\text{cw-sic}} \in \mathbb{C}^{N_R \times N_R}$ , needs to be updated according to the modified received signal. A standard way to define a cancellation order is to select the strongest signal based on a predefined metric, e.g. signal-to-interference-and-noise (SINR) values at the output of the LMMSE filter. The strongest signal can be selected by computing  $[x^*, q^*, l^*] = \arg \max_{x,q,l} (Y_{n_k,x_q,l}) \quad \forall x \in \mathcal{B}^{\text{dom}}, \forall q \in \mathcal{U}_x^{\text{dom}}, \forall l \in \mathcal{S}_q^{\text{dom}}$ . Consequently, the sets need to be updated for the next successive stage accordingly:  $\mathcal{B}^{\text{dom}} = \{\mathcal{B}^{\text{dom}} \setminus x^*\}$ ,  $\mathcal{U}_x^{\text{dom}} = \{\mathcal{U}_x^{\text{dom}} \setminus q^*\}$ ,  $\mathcal{S}_q^{\text{dom}} = \{\mathcal{S}_q^{\text{dom}} \setminus l^*\}$ . After the LMMSE filtering, the estimated data symbols,  $\hat{\mathbf{b}}_{x_q,l}$ , associated with the strongest signal are converted to bit-level information, same way as with the LMMSE-IRC, to be decoded by the turbo decoder. Then, the estimate of the strongest signal component is reconstructed by exploiting the output of the turbo decoder and subtracted from the modified received signal on all considered subcarriers/PRB by

$$\check{\mathbf{r}}_{n_k}^{\text{cw-sic}} = \check{\mathbf{r}}_{n_k}^{\text{cw-sic}} - \mathbf{H}_{n_k,x^*} \mathbf{t}_{x_q^*,l^*} \bar{\mathbf{b}}_{x_q^*,l^*}^{\text{cw}} \quad (15)$$

where,  $\bar{b}_{x_q^*, l}^{cw}$  represents a reconstructed modulated data symbol based on a decoded codeword associated with the strongest signal. This procedure is repeated, until the all data streams associated to a desired signal are detected or a point is achieved where it is not possible to continue a successive detection. It is worth noting that the codeword based scheme introduces an additional delay, due to the turbo decoding, to the successive detection process. Furthermore, a straightforward extension of this scheme is to replace the LMMSE filter with the WMMSE filter introduced in Section 3.1.2.

#### 4.2.1.2 Symbol based LMMSE-SIC

In this subsection, a modulation symbol based LMMSE-SIC is briefly considered. In general, the codeword and the modulation symbol based schemes follow the same successive cancellation principle. Therefore, we highlight here only key differences between the schemes.

In contrast to the codeword approach, the symbol based LMMSE-SIC performs successive linear filtering and the subtraction of the strongest signal on the modified received signal  $\tilde{\mathbf{r}}_{n_k}^{\text{mod-sic}} \in \mathbb{C}^{N_R}$  at modulation symbol basis. Hence, the coefficients of the LMMSE filter  $\mathbf{w}_{n_k, x_q, l}^{\text{symb-sic}} \in \mathbb{C}^{N_R}$  for the symbol based SIC needs to be computed for each modulation symbol as follows

$$\mathbf{w}_{n_k, x_q, l}^{\text{symb-sic}} = \boldsymbol{\Sigma}_{n_k}^{\text{symb-sic}^{-1}} \mathbf{H}_{n_k, x} \mathbf{t}_{x_q, l} \bar{\sigma}_{x_q, l}^2, \forall x \in \mathcal{B}^{\text{dom}}, \forall q \in \mathcal{U}_x^{\text{dom}}, \forall l \in \mathcal{S}_q^{\text{dom}} \quad (16)$$

where the estimate of the interference covariance matrix  $\boldsymbol{\Sigma}_{n_k}^{\text{cw-sic}} \in \mathbb{C}^{N_R \times N_R}$  for the symbol based SIC scheme needs to be updated according to the modified received signal. Additionally, the sets  $\mathcal{B}^{\text{dom}}$ ,  $\mathcal{U}_x^{\text{dom}}$  and  $\mathcal{S}_q^{\text{dom}}$  need to also be updated on a modulation symbol basis. The modified received signal is obtained by subtracting the reconstructed strongest signal component by exploiting the output of the LMMSE filter which is given by

$$\tilde{\mathbf{r}}_{n_k}^{\text{symb-sic}} = \tilde{\mathbf{r}}_{n_k}^{\text{symb-sic}} - \mathbf{H}_{n_k, x} \mathbf{t}_{x_q^*, l} \bar{b}_{x_q^*, l}^{\text{mod}} \quad (17)$$

where,  $\bar{b}_{x_q^*, l}^{\text{mod}}$  represents a reconstructed modulated data symbol based on the output of the LMMSE filter associated with the strongest signal. It is worth noting that by using the symbol based SIC additional delay is not introduced compared to the codeword based SIC. Also, the symbol based SIC does not benefit from coding gain as opposed to the codeword based SIC.

#### 4.2.2 Maximum Likelihood Based Joint Detection

In general, in contrast to the LMMSE-SIC scheme, the target of a joint detection is to jointly detect desired as well as interfering signals. Particularly, we focus on a maximum likelihood (ML) based joint detector that performs the joint detection of desired and interferer signals in a spatial domain. Here,  $\mathcal{J}$  defines the set of jointly detected signals. By assuming equally probable transmitted bits, log-likelihood ratio at the  $z^{\text{th}}$  bit position  $z \in \{1, \dots, Q^{\text{tot}}\}$ , where  $Q^{\text{tot}}$  denotes the total number of jointly detected bits, for the ML based spatial domain joint detector associated with the  $k^{\text{th}}$  UE served the  $n^{\text{th}}$  BS, can be written as

$$\mathcal{L}_{n_k}^z = \ln \frac{\sum_{\mathbf{b}: [\mathbf{b}]_z \in \mathcal{C}^0} \exp(-(r_{n_k} \cdot \tilde{\mathbf{H}}_{n_k} \mathbf{b})^H \boldsymbol{\Sigma}_{n_k}^{\text{ML}^{-1}} (r_{n_k} \cdot \tilde{\mathbf{H}}_{n_k} \mathbf{b}))}{\sum_{\mathbf{b}: [\mathbf{b}]_z \in \mathcal{C}^1} \exp(-(r_{n_k} \cdot \tilde{\mathbf{H}}_{n_k} \mathbf{b})^H \boldsymbol{\Sigma}_{n_k}^{\text{ML}^{-1}} (r_{n_k} \cdot \tilde{\mathbf{H}}_{n_k} \mathbf{b}))} \quad (18)$$

where  $\tilde{\mathbf{H}}_{n_k} \in \mathbb{C}^{N_R \times |\mathcal{J}|}$  represents a stacked effective frequency domain channel matrix, i.e. channel and precoding included, for the joint detection of  $|\mathcal{J}|$  signals associated with  $k^{\text{th}}$  UE served by the  $n^{\text{th}}$  BS and  $\tilde{\mathbf{b}} \in \mathbb{C}^{|\mathcal{J}|}$  defines a candidate symbol vector for jointly detected signals. The sets  $\mathcal{C}^0$  and  $\mathcal{C}^1$  denote the subset of constellation candidates for the jointly detected signals whose bit is 0 and 1, respectively. The matrix  $\boldsymbol{\Sigma}_{n_k}^{\text{ML}} \in \mathbb{C}^{N_R \times N_R}$  is the estimate of an interference covariance matrix which includes interfering signal components being not jointly detected. Note that depending on the applied signal processing at the receiver, the interference covariance matrix can have either non-diagonal or diagonal structure.

It is worth noting that the above equation represents the optimum joint detection in a ML sense over a jointly detected signal space. However, the approach comes at cost of prohibitively high computational complexity which grows exponentially in terms of the total number of number of jointly detected signals with respect to the associated constellation alphabets.

## 5 Discussion on Computational Complexity Comparison

In this section, the computational complexity of each candidate detector is discussed. Since our focus is not on any specific processor architecture, the number of multiplication and division are omitted from this evaluation due their possible dependence on the considered architecture. Instead of this, we characterize complexity of the candidate detection schemes by using the  $O$ -notation. Furthermore, issues related to the memory consumptions and processing delay of the candidate schemes are also neglected from the consideration.

Table 1 provides a summary of the estimated computational complexity of Rel-12 candidate MIMO signal detection schemes. To ease the comparison between different detection schemes, the complexity comparison is provided per modulated data symbol. It is worth noting that for the LMMSE-IRC, W-LMMSE-IRC and the codeword based LMMSE-SIC, the filter coefficients may be updated e.g. per sub-band/PRB basis. On the contrary, for the symbol based LMMSE-SIC filter coefficients need to be computed for each modulation symbol. In the same way, ML based approach calculates also the decision metric for each bit of every modulated data symbols. As can be observed, both LMMSE-SIC schemes and LMMSE-IRC detectors have a cubic order complexity in terms of number of receiver antennas. The cubic order complexity becomes from the matrix inversion of the interference covariance matrix. On the contrary, the W-LMMSE-IRC requires twice the amount of arithmetical operations with respect to the LMMSE-IRC. However, due to this limited increase in the complexity, the computational complexity of W-LMMSE-IRC can be still considered to be of the same order as the LMMSE-IRC. The sequential behaviour of LMMSE-SIC based detectors scale linearly with the number of subsequent stages  $S$ . It is worth also noting that the computational complexity of the turbo decoder is not specifically addressed. Since the codeword based LMMSE-SIC exploits the turbo decoder in subsequent cancellation stages, its computational complexity is assumed to be higher compared to the symbol based LMMSE-SIC. As can be observed, the computational complexity of ML approaches grows exponentially to the total number of jointly detected signals,  $|J|$ . Here,  $M$  denotes the size of modulation alphabet. The exponential complexity with respect to the modulation alphabet size comes from the necessity to compute a decision metric involving an exponentially growing number of hypotheses.

Based on the above discussion, we categorize the Rel-12 candidate detectors to belong into low, medium and high complexity classes as follows: low complexity: LMMSE-IRC, W-LMMSE-IRC and symbol based LMMSE-SIC, medium: codeword based LMMSE-SIC, high: ML

Table 1. Summary of complexity estimates of each Rel-12 candidate detection schemes. Green, yellow and red colors correspond to low, medium, and high computational complexity, respectively.

Candidate detector	Estimate of computational complexity per modulated data symbol	Complexity class
LMMSE-IRC	$O(N_R^3)^{(1)}$	low
W-LMMSE-IRC	$O(2N_R^3)^{(1)}$	low
Symbol based LMMSE-SIC	$O(SN_R^3)^{(2)}$	low
Codeword based LMMSE-SIC	$O(SN_R^3)^{(1)}$	medium
ML	$O(M^{ J })^{(3)(4)}$	high

<sup>(1)</sup> coefficients need to be update per PRB/sub-band

- (2) coefficients need to be update per modulation symbol
- (3) decision metric needs to be calculated for each modulation symbol
- (4) It is assumed that all jointly detected signals use same modulation alphabets.

**Observation 1:** LMMSE-IRC, WMMSE-IRC and symbol based LMMSE-SIC are considered to have low computational complexity

**Observation 2:** Codeword based LMMSE-SIC is considered to have medium computational complexity

**Observation 3:** ML based joint detection is considered to have prohibitively high computational complexity

## 6 Discussion on the Feasibility of Candidate Detectors

In this section the feasibility aspects of different candidate detectors for Rel-12 are considered.

Table 2 provides a summary of key parameters for the feasibility evaluation.

Table 2. Summary of key parameters for the feasibility evaluation of Rel-12 candidate detection schemes. Green, yellow and red colors indicates low, medium, and high feasibility for Rel-12 candidate detector, respectively.

Candidate Detection Scheme	Required information for detection					Channel coding interferer	Processing complexity	Capability to mitigate number of interferers
	Channel of intended signal	Channel of interfering signal	Effective channel of interfering signal <sup>(4)</sup>	Interference covariance matrix type <sup>(2)</sup>	Modulation scheme of interfering signal			
LMMSE-IRC	Yes	No	No	Non-diagonal	No	No	Low	$N_R-1$
WMMSE-IRC	Yes	No	No	Non-diagonal	No	No	Low	$2N_R-1$
Symbol based LMMSE-SIC	Yes	Yes	Yes	<sup>(3)</sup> Non-diagonal	Yes	No	Low	$N_R-1$
Codeword based LMMSE-SIC	Yes	Yes	Yes	Non diagonal	Yes	Yes	Medium	$N_R-1$
ML	Yes	Yes	Yes	Diagonal <sup>(1)</sup>	Yes	No	High	$N_R$

<sup>(1)</sup> The diagonality of matrix depends on the accounted number of interferers and applied signal processing techniques.

<sup>(2)</sup> Depending on a transmission mode, interference covariance matrix estimate may be obtained from CRS or DM-RS.

<sup>(3)</sup> In the strict sense, this does not hold when all interferers have been cancelled out from a received signal.

<sup>(4)</sup> This depends on the considered transmission mode. Here, TM10 is assumed and effective channels for desired and interference signals are directly obtained from DM-RS channel estimates.

<sup>(5)</sup> Here, an effective channel refers to a channel seen at a receiver after impact of channel and precoding.

Based on the aforementioned summary table, we make following observations and proposals:

**Observation 4:** *WMMSE-IRC can enhance the interference suppression capability of linear interference-aware detector in terms of number of mitigated interferers, from  $N_{R-1}$  to  $2N_{R-1}$ , leading to an improved performance in interference limited scenarios*

**Proposal 2:** *LMMSE-IRC detector has to be used as benchmark detector for all consider further enhancements in Rel-12 framework.*

**Proposal 3:** *WMMSE-IRC should be included as one candidate detector for further enhancement in Rel. 12*

**Proposal 4:** *Codeword based LMMSE-SIC scheme provides a reasonable complexity and performance tradeoff, it should be selected as a reference detector for Rel-12 work on NAISC for RAN4*

**Proposal 5:** *ML based joint detection is seen to have a prohibitively high computational complexity and should not be considered further*

---

## 7 Conclusions

In this contribution, interference-aware linear and non-linear MIMO signal detection strategies for LTE Rel-12 have been described. Additionally, the complexity and feasibility aspects of the Rel-12 candidate schemes have been covered, Our observations and proposals are as follows:

**Observation 1:** *LMMSE-IRC, WMMSE-IRC and symbol based LMMSE-SIC are considered to have low computational complexity*

**Observation 2:** *Codeword based LMMSE-SIC is considered to have medium computational complexity*

**Observation 3:** *ML based joint detection is considered to have prohibitively high computational complexity*

**Observation 4:** *WMMSE-IRC can enhance the interference suppression capability of linear interference-aware detector in terms of number of mitigated interferers, from  $N_{R-1}$  to  $2N_{R-1}$ , leading to an improved performance in interference limited scenarios*

**Proposal 1:** *Complexity assessment of the candidate detectors should consider factors like interference structure availability, number of desired and interfering streams as well as the potential introduction of 256 QAM.*

**Proposal 2:** *LMMSE-IRC detector has to be used as benchmark detector for all consider further enhancements in Rel-12 framework.*

**Proposal 3:** *WMMSE-IRC should be included as one candidate detector for further enhancement in Rel. 12*

**Proposal 4:** *Codeword based LMMSE-SIC scheme provides a reasonable complexity and performance tradeoff, it should be selected as a reference detector for Rel-12 work on NAISC for RAN4*

**Proposal 5:** *ML based joint detection is seen to have a prohibitively high computational complexity and should not be considered further*

.

---

## References

- [1] RP-130404, *Study on Network-Assisted Interference Cancellation and Suppression for LTE*, MediaTek Inc., Renesas Mobile Europe Ltd, Broadcom Corporation, Orange, RIM, Telefonica, CHTTL, Magnolia Broadband, US Cellular, Verizon Wireless, China Telecom, China Mobile, T-Mobile USA, Intel, Deutsche Telekom, Telecom Italia, Alcatel-Lucent, Alcatel-Lucent Shanghai Bell, Qualcomm, Huawei, HiSilicon, Sprint, ZTE, China Unicom, Lightsquared, CATR, Samsung, Ericsson, ST Ericsson, CATT, Softbank Mobile
- [2] R1-131376, *Scenarios for network assisted interference cancellation and suppression*, Renesas Mobile Europe Ltd
- [3] R4-131792, *Further considerations on Advanced Receivers*, Renesas Mobile Europe Ltd
- [4] TR 36.829, “Enhanced Performance Requirements for LTE User Equipment (UE)”, Release 11, v11.1.0 (2012-12),