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Title: **Further Discussion on Receiver Structure Feasibility for LTE Rel-12**

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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 (NAICS) for LTE UE [1]. During RAN4#66-bis, discussion on the feasibility of different receivers for Rel.12 has been initiated. As a outcome of RAN4#66-bis, companies have been asked to recategorize their proposed receiver structures according to a way forward (WF) message on the NAICS receiver terminology[5]. In this contribution, we provide recategorization of our proposed receiver candidates according to [5].

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 witih 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 when the needed information is implicitly at the UE. From this perspective RAN4 would need to asses the gains of more advanced demodulation and decodig stuctures. The cases of intra-cell 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 introdution 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 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 nth 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 kth UE served by the nth 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:

$$\mathbf{r}_{n_k} = \mathbf{H}_{n_k,n}\mathbf{t}_{n_{k,d}}b_{n_k,d} + \mathbf{H}_{n_k,n}\sum_{s\subset\mathcal{S}_{n_{k\backslash d}}}\mathbf{t}_{n_{k,s}}b_{n_k,d} + \mathbf{H}_{n_k,n}\sum_{j\subset U_{n\backslash k}}\sum_{l\subset\mathcal{S}_{n_j}}\mathbf{t}_{n_{j,l}}b_{n_j,l} + \sum_{m\subset\mathcal{B}\backslash n}\mathbf{H}_{n_k,m}\sum_{i\subset U_m}\sum_{v\subset\mathcal{S}_{n_i}}\mathbf{t}_{m_{i,v}}b_{m_i,v} + \mathbf{n}_{n_k} \quad (1)$$

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 kth UE and the nth BS. The vector $\mathbf{t}_{n_k,d} \in \mathbb{C}^{N_T}$ denotes precoder for the dth data stream of the kth UE associated with the nth serving BS and $\mathcal{S}_{n_k\ nk}$ describes the set of data streams for the kth UE associated with the nth BS. The scalar $b_{n_k,d}$ represent modulated data symbol for the dth data stream of the kth 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). According to WF on NAICS receiver terminology in RAN4-66bis [5], the detector structures have been decided to be categorized into three different categories, namely, interference suppression (IS), interference cancellation (IC) and ML. The first category consists of IS based detectors such as linear minimum mean square error (LMMSE)-IRC, enhanced (E)-LMMSE-IRC and widely (W)-LMMSE-IRC. Then, the second category includes IC based detectors such as linear code word (CW) level SIC (L-CWIC), ML-CWIC, symbol level IC (SLIC) as well as parallel interference cancellation (PIC) based detectors. Finally, the third category comprises of ML schemes such as full-blown ML, reduced complexity ML (R-ML) and iterative versions of ML (=MAP) and R-ML.

The proposed categorization, provided in [5], leads to inconsistency in the terminilogy. The reason for this is two fold: Firstly, the terminology of both IS and IC refer to the functionality of a considered scheme. However, the ML refers directly to the actual optimization criterion of a considered scheme rather than its functionality. Secondly, both ML and MAP based schemes have been categorized under ML detectors. However, maximum a posteriori (MAP) and ML based detectors lead to completely different realizations of the detector structure. In general, the MAP criterion based detectors can be considered as iterative detectors in which a priori information about the probability of transmitted bits is exploited. On the contrary, the ML criteria based detectors can be considered as non-iterative "one-shot" detectors in which a priori information of transmitted bits is not used. It is worth noting that the equivalency between the MAP and the ML criteria based detectors holds only in a special case when a priori probabilities of transmitted bits are equivalent.

Observation 1: The proposed categorization leads to inconsistency in the terminilogy. Therefore, the terminology for the categorization of detectors provided in [5] needs to be modified.

Instead of the ML category, joint detection (JD) could be used as a category to be in line with both IS and IC categories. Furthermore, the JD can encapsulate both ML and MAP criteria without any problems. Based on observation provided above, we propose the following modification to furher clarify the current categorization

Proposal 2: The ML category is proposed to be replaced with joint detection (JD) category.

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 IS Detectors

In this subsection, IA linear IS based 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 dth data stream $\hat{b}_{n_k,d}$ can be expressed as

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

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

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

where $\bar{\bar{\sigma}}^2_{n_k,d}$ represents the power of a modulation symbol, and $\mathbf{\Sigma}_{n_k}{}^{\text{IRC}} \in \mathbb{C}^{N_R \times N_R}$ 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 (WLMMSE-IRC)

In this subsection, a WLMMSE-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 WLMMSE-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:

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

where

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

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

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

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

$$\tilde{\mathbf{n}}_{\boldsymbol{n_k}} = \mathbf{H}_{\boldsymbol{n_k},\boldsymbol{n}} \sum_{s \subset \mathcal{S}_{n_k \setminus d}} \mathbf{t}_{n_{k,s}} b_{n_k,d} + \mathbf{H}_{n_k,n} \sum_{j \subset U_{n \setminus k}} \sum_{\boldsymbol{l} \subset \boldsymbol{\mathcal{S}_{n_j}}} \mathbf{t}_{\boldsymbol{n_j},\boldsymbol{l}} b_{n_j,l} + \sum_{m \subset \mathcal{B} \setminus n} \mathbf{H}_{n_k,m} \sum_{i \subset U_m} \sum_{v \subset \mathcal{S}_{n_i}} \mathbf{t}_{m_{i,v}} b_{m_i,v} + \mathbf{n}_{n_k} \mathbb{C}^{N_R} \quad (9)$$

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

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

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

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

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

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

*w*here $\mathbf{C}_{bb} = E\left[\mathbf{b}_{n_k,d}^{\mathrm{A}} \mathbf{b}_{n_k,d}^{A}{}^{\mathrm{T}}\right] \in \mathbb{R}^{2\times 2}$ 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 WLMMSE-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 IC Detectors

In this subsection, interference-aware IC based detectors are discussed. Particularly, 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 sequently 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 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 sequently 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 $\check{\mathbf{r}}_{n_k}^{\mathrm{cw-sic}} \in \mathbb{C}^{N_R}$ 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

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

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

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

As can be noted, the filter coefficients need to be computed for all combinations defined by the sets $\mathcal{B}^{\mathrm{dom}}$, $\mathrm{U}_x^{\mathrm{dom}}$ and $\mathrm{S}_q^{\mathrm{dom}}$ 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, $\mathbf{\Sigma}_{n_k}^{\mathrm{cw-sic}} \in \mathbb{C}^{N_R \times N_R}$, 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 $[x^*, q^*, l^*] = \arg\max_{x,q,l}(\gamma_{n_k,x_q,l}) \quad \forall x \in \mathcal{B}^{\mathrm{dom}}, \forall q \in \mathrm{U}_x^{\mathrm{dom}}, \forall l \in \mathrm{S}_q^{\mathrm{dom}}$. Consequently, the sets need to be updated for the next successive stage accordingly: $\mathcal{B}^{\mathrm{dom}} = \{\mathcal{B}^{\mathrm{dom}} \backslash x^*\}$, $\mathrm{U}_x^{\mathrm{dom}} = \{\mathrm{U}_x^{\mathrm{dom}} \backslash q^*\}$, $\mathrm{S}_q^{\mathrm{dom}} = \{\mathrm{S}_q^{\mathrm{dom}} \backslash l^*\}$. After the LMMSE filtering, the estimated data symbols, $\hat{b}_{x_q,l}$, 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

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

where, $\bar{\bar{b}}_{x_{q^*}^*,l^*}^{\mathrm{cw}}$ 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 WLMMSE filter introduced in Section 3.1.2.

4.2.2 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 $\check{\mathbf{r}}_{n_k}^{\mathrm{mod-sic}} \in \mathbb{C}^{N_R}$ at modulation symbol basis. Hence, the coefficients of the LMMSE filter $\mathbf{w}_{n_k,x_q,l}{}^{\mathrm{symb-sic}} \in \mathbb{C}^{N_R}$ for the symbol based SIC needs to be computed for each modulation symbol as follows

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

where the estimate of the interference covariance matrix $\mathbf{\Sigma}_{n_k}^{\mathrm{cw-sic}} \in \mathbb{C}^{N_R \times N_R}$ for the symbol based SIC scheme needs to updateted according to the modified received signal. Additionally, the sets $\mathcal{B}^{\mathrm{dom}}$, $\mathrm{U}_x^{\mathrm{dom}}$ and $\mathrm{S}_q^{\mathrm{dom}}$ need to also 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

$$\check{\mathbf{r}}_{n_k}^{\mathrm{symb-sic}} = \check{\mathbf{r}}_{n_k}^{\mathrm{symb-sic}} - \mathbf{H}_{n_k,x^*} \mathbf{t}_{x_{q^*}^*,l^*} \bar{\bar{b}}_{x_{q^*}^*,l^*}^{\mathrm{mod}} \quad (17)$$

where , $\bar{\bar{b}}^{\text{mod}}_{x^*_{q^*},l^*}$ 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.

4.3 Joint Detection Based MIMO Detectors

This section focuses on MIMO signal detection schemes which perform joint detection of desired as well as interfering signals in a spatial domain. A special focus is given on ML and MAP optimization criteria based detectors.

4.3.1 Maximum Likelihood Based Joint Detection

In this subsection, we consider a maximum likelihood (ML) based joint detector that performs the joint detection of desired and interferer signals in a spatial domain. In the following, the computation of the bit-level soft information, for the output of ML criterion based joint detector is described. By assuming equally probable estimates of transmitted bits, log-likelihood ratio (LLR), $\mathcal{L}^{(z),\text{ML}}_{n_k}$, at the output of ML based joint detector, for kth UE served by the nth BS associated with the zth bit position $z \in \{1, \dots, Q^{\text{tot}}\}$, where Q^{tot} denotes the total number of jointly detected bits, can be computed as

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

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^{th} UE served by the nth BS and $\tilde{\mathbf{b}}$ $\mathbb{C}^{|\mathcal{J}|}$,defines a candidate symbol vector for jointly detected signals. Here, $\mathcal{J}$ defines the set of 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 $\mathbf{\Sigma}^{\text{ML}}_{n_k} \in \mathbb{C}^{N_R \times N_R}$ is the estimate of an interference covariance matrix for the ML criterion based joint detector 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.

4.3.2 Maximum a Posteriori Based Joint Detection

In this section, the MAP criterion based spatial domain joint detector is briefly described. Generally, MAP criterion based spatial domain joint detectors follow the turbo-principle [6] in which extrinsic soft-information is exchanged iteratively between detection and a channel decoding blocks.

In contrast to the ML criterion based approach, feedback information from a channel decoder is incoperated to a decision metric in a form of a priori information of transmitted bits. By using (18), the extrinsic LLR,$\mathcal{L}^{(z),\text{MAP}}_{n_k}$, at the output of the MAP criterion based detector for the kth UE served by the nth BS associated with the zth bit position can be calculated as

$$\mathcal{L}^{(z),\text{MAP}}_{n_k} = \ln \frac{\sum_{\tilde{\mathbf{b}}:[\tilde{\mathbf{b}}]_z \in \mathcal{C}^0} \exp\left(-(\mathbf{r}_{n_k} - \tilde{\mathbf{H}}_{n_k}\tilde{\mathbf{b}})^{\mathbf{H}} \mathbf{\Sigma}^{\text{MAP}^{-1}}_{n_k} (\mathbf{r}_{n_k} - \tilde{\mathbf{H}}_{n_k}\tilde{\mathbf{b}})\right) \exp\left(\sum_{m \epsilon Q \setminus z} \mathcal{L}^{(m),\text{apriori}}_{n_k}\right)}{\sum_{\tilde{\mathbf{b}}:[\tilde{\mathbf{b}}]_z \in \mathcal{C}^1} \exp\left(-\left(\mathbf{r}_{n_k} - \tilde{\mathbf{H}}_{n_k}\tilde{\mathbf{b}}\right)^{\mathbf{H}} \mathbf{\Sigma}^{\text{MAP}^{-1}}_{n_k} (\mathbf{r}_{n_k} - \tilde{\mathbf{H}}_{n_k}\tilde{\mathbf{b}})\right) \exp\left(\sum_{m \epsilon Q \setminus z} \mathcal{L}^{(m),\text{apriori}}_{n_k}\right)} \quad (19)$$

Where $\mathcal{L}^{(m),\text{apriori}}_{n_k}$ denotes a priori LLR of transmitted bits for the kth UE served by the nth BS associated with the mth bit position. Q defines the set for jointly detected signals in a bit domain. The matrix $\mathbf{\Sigma}^{\text{MAP}}_{n_k} \in \mathbb{C}^{N_R \times N_R}$ is the estimate of an interference covariance matrix for the MAP criterion based joint detector which includes interfering signal

components being not jointly detected. It is worth noting that depending on the applied signal processing at the receiver, the interference covariance matrix can have either non-diagonal or diagonal structure.

In general, the MAP based spatial domain detector provides an upper bound performance to a joint detection problem of desired and interfering signals. However, the computational complexity of the MAP based joint detector is intractable and remains at the same level as with the ML. Additionally, it is worth noting that due the iterative nature of the MAP based detection procedure, an additional processing delay needs to be taken into account while considering its computational complexity.

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 WLMMSE-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 WLMMSE-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, $|\mathcal{J}|$. 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 explonentially growing number of hypotheses. To reduce the exponential computational complexity of the ML based joint detection, the Sphere detection can be considered. The computational complexity of the Sphere decoding algorithm is proportional to the number of visited nodes on a search tree i.e. number of points inside of sphere with a given radius and number of jointly detected signals. It is worth noting that the radius of the sphere depends heavily on the operation point of detector [7]. Therefore, there is no fixed computational complexity available for the Sphere detector with an adaptive radius.In [7], it is shown that the average computational complexity of the Sphere detector is polynomial. Finally, it can be observed that the computational complexity of the MAP criterion based joint detection scheme is exponential. Hence, the MAP based scheme can be considered as an intractable from the pragmatic implementation point of view.

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, WLMMSE-IRC and symbol based LMMSE-SIC, medium: codeword based LMMSE-SIC, high: Sphere, ML and MAP.

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
WLMMSE-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
Sphere (ML-based)	Polynomial on average [(6),(7)]	high
ML	$O(M^{\lvert\mathcal{J}\rvert})$ [(3) (4)]	high
MAP	$O(IM^{\lvert\mathcal{J}\rvert})$ [(3) (4)(5)]	high

(1) 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.

(5) *I* defines the number of iterations between the detection and channel decoding stages.

(6) The complexity of the sphere decoding algorithm is proportional to the number of visited nodes on a search tree i.e. number of points inside of sphere with a given radius and number of jointly detected signals. The radius of the Sphere depends heavily on the operation point of detector [7].

(7) This value reflects the computational complexity of ML- based sphere detector on average.

Observation 2: *LMMSE-IRC, WLMMSE-IRC and symbol based LMMSE-SIC are considered to have low computational complexity.*

Observation 3: *Codeword based LMMSE-SIC is considered to have medium computational complexity.*

Observation 4: *ML based joint detection is considered to have prohibitively high computational complexity.*

Observation 5: *MAP based joint detection is considered as intractable due to its exponential computational complexity.*

Observation 6: The computational complexity of Sphere detector is polynomial on average.

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						Processing complexity	Capability to mitigate number of interferers
	Channel of intended signal	Channel of interfering signal	Effective channel of interfering signal [4]	Interference covariance matrix type [2]	Modulation scheme of interfering signal	Channel coding interferer		
LMMSE-IRC	Yes	No	No	Non-diagonal	No	No	Low	N_R-1
WLMMSE-IRC	Yes	No	No	Non-diagonal	No	No	Low	$2N_R$-1
Symbol based LMMSE-SIC	Yes	Yes	Yes	[3]Non-diagonal	Yes	No	Low	N_R-1
Codeword based LMMSE-SIC	Yes	Yes	Yes	Non diagonal	Yes	Yes	Medium	N_R-1
Sphere	Yes	Yes	Yes	Diagonal[1]	Yes	No	High	N_R
ML	Yes	Yes	Yes	Diagonal[1]	Yes	No	High	N_R
MAP	Yes	Yes	Yes	Diagonal[1]	Yes	Yes	High	N_R

[1] The diagonality of matrix depends on the accounted number of interferers and applied signal processing techniques.

[2] Depending on a transmission mode, interference covariance matrix estimate may be obtained from CRS or DM-RS.

[3] In the strict sense, this does not hold when all interferers have been cancelled out from a received signal.

[4] 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.

[5] 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 7: *WLMMSE-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: The ML category is proposed to be replaced with joint detection (JD) category.

Proposal 3: *LMMSE-IRC detector has to be used as benchmark detector for all consider further enhancements in Rel-12 framework.*

Proposal 4: *WLMMSE-IRC should be included as one candidate IS detector for further enhancement in Rel. 12.*

Proposal 5: *Codeword based LMMSE-SIC scheme provides a reasonable complexity and performance tradeoff, it should be selected as a reference IC detector for Rel-12 work on NAISC for RAN4.*

Proposal 6: *ML based joint detection is seen to have a prohibitively high computational complexity and can be depriorized.*

Proposal 7: *Due to the average polynomial computational complexity of the Sphere detector, it is not seen as attractive scheme for practical implementation and can be depriorized.*

Proposal 8: *MAP based joint detection is seen to have a prohibitively high computational complexity and can be depriorized.*

7 Conclusions

In this contribution, interference-aware IS, IC and joint detection based MIMO signal detection strategies for LTE Rel-12 have been briefly 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: The proposed categorization leads to inconsistency in the terminilogy. Therefore, the terminology for the categorization of detectors provided in [5] needs to be modified.

Observation 2: *LMMSE-IRC, WLMMSE-IRC and symbol based LMMSE-SIC are considered to have low computational complexity.*

Observation 3: *Codeword based LMMSE-SIC is considered to have medium computational complexity.*

Observation 4: *ML based joint detection is considered to have prohibitively high computational complexity.*

Observation 5: *MAP based joint detection is considered as intractable due to its exponential computational complexity.*

Observation 6: The computational complexity of Sphere detector is polynomial on average.

Observation 7: *WLMMSE-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: The ML category is proposed to be replaced with joint detection (JD) category.

Proposal 3: *LMMSE-IRC detector has to be used as benchmark detector for all consider further enhancements in Rel-12 framework.*

Proposal 4: *WLMMSE-IRC should be included as one candidate IS detector for further enhancement in Rel. 12.*

Proposal 5: *Codeword based LMMSE-SIC scheme provides a reasonable complexity and performance tradeoff, it should be selected as a reference IC detector for Rel-12 work on NAISC for RAN4.*

Proposal 6: *ML based joint detection is seen to have a prohibitively high computational complexity and can be depriorized.*

Proposal 7: *Due to the average computation complexity of the Sphere detector, it is not seen as attractive scheme for practical implementation and can be depriorized.*

Proposal 8: *MAP based joint detection is seen to have a prohibitively high computational complexity and can be depriorized.*

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