Scenario Independent IRC Receiver with SFBC for MBMS over Single Frequency Network

Hongzhi Chen, Alexandr M. Kuzminskiy, Pei Xiao, Rahim Tafazolli
5G Innovation Center, University of Surrey, UK
(hongzhi.chen,a.kuzminskiy,p.xiao,r.tafazolli)@surrey.ac.uk

***Abstract*—In the current Long Time Evolution (LTE) broadcast systems i.e. enhanced Multimedia Broadcast Multicast Service (eMBMS) with Single Frequency Network (MBSFN), MBSFN service area edge users may still suffer interference from the adjacent MBSFN or non-MBSFN services which have detrimental effects on the broadcast service spectrum's efficiency as the data rate of a broadcast/multicast system is decided by the receiver with the worst Signal to Interference plus Noise Ratio (SINR). In this paper, we consider a scenario independent[1] interference rejection combining receiver with regularisation to any user with the SINR below a certain threshold, based on a bottom-up concept, that should increase the overall broadcast system spectrum efficiency. The bit error rate results demonstrate that it has a stable performance in both noise-limited and interference-limited scenarios. Space-Frequency Block Coding (SFBC) is used on the transmitter side to increase the transmitter diversity, on top of the existing macro-diversity achieved by MBSFN transmissions. It provides a potential solution for concurrent transmissions of different adjacent MBSFN services at the same time which is currently only supported in a Time Division Multiple Access (TDMA) manner.**

***Index Terms*—Multicast broadcast single frequency network (MBSFN), SINR, Interference rejection combining (IRC), Regularisation, Time division multiple access (TDMA).**

I. Introduction

The evolved Multimedia Broadcast Multicast Service (eMBMS) has been standardized in Third-Generation Partnership Project (3GPP) release 9 [1] and further updated recently in release 14 [2] in order to cope with the ever-growing demand of various data requirements. Current mobile communication systems are facing great pressure from the increase in service capacity and more efficient use of the spectrum. In eMBMS, a group of cells are allowed to operate on the same frequency and transmit the same data simultaneously so users can obtain better reception by collecting combined signals. This group of cells is called a Multicast Broadcast Single Frequency Network (MBSFN) [1], [3], [4].

eMBMS provides LTE based broadcast/multicast service, the bottleneck at the transmitter side is introduced in [5]. On the receiver side, the broadcast operating data rate is limited by the worst signal quality received by the user [6] $i.e.$ the user with the lowest Signal-to-Interference Noise Ratio (SINR). A bottom-up approach considering the increasing of the worst users' SINR leads to the design of interference-aware receivers [7]. eMBMS is a subsystem of LTE which means that all the receivers should have at least two antennas and [8] support diversity combining techniques.

The IRC receiver, based on the Minimum Mean Square Error (MMSE) criteria, requires accurate estimation of the interference plus noise covariance matrix with a limited number of downlink pilot symbols. To offset the estimation error, [9] has proposed a scenario independent solution using regularisation on the interference plus noise covariance matrix; This solution ensures the IRC receiver has stable performance in different environments $i.e.$ different SINR scenarios and receiver parameters. [9] shows some simulation results in an LTE interference scenario to demonstrate its effectiveness. However, no transmitter diversity method has been used in [9], which under MBSFN multi-cell processes transmitter diversity situation. This is a direction worth considering. On the other hand, due to the synchronism transmission feature of different MBSFN transmitter antennas, each of them transmit the same frame through antenna port 4 [10] with the same pilot symbols at the same position. The receiver is aware to how many MBSFN cells attend the transmission but treats the received signal as if it comes from a big cell with multipath fading (with extended cyclic prefix). In order to maximise the eigenvalue of the IRC covariance matrix, a re-designed orthogonal pilot pattern for MBSFN is given in this paper. The transmitter diversity is achieved by employing Space-Frequency Block Coding (SFBC) with the Alamouti coding [11], mainly applied to users located at the cell/area edge which fits our target user location. Moreover, both transmitter and receiver diversity can be exploited in order to further increase the system performance in comparison to [9].

In the rest of the paper, Section II formulates the system model and the existing problem, regularisation-based interference plus noise covariance estimation with SFBC diversity transmission to calculate the IRC weight matrix. Section III presents the simulation results in the MBSFN downlink scenario including comparison with an empirical solution to prove its independence. Section IV concludes the paper.

II. Problem Formulation

A. System Model

In this paper, the MBSFN transmission comprises two transmitter cells to achieve the maximum transmit diversity gain when SFBC with Alamouti coding is employed in the spatial domain. Each cell is responsible for one bunch of the

[1]The SINR value can be comprised of different combinations of interference and noise as well as differernt receiver parameters and the receiver should work stably in any given situation

SFBC precoded signal stream. Two essential assumptions are made for the system:

- There are sufficient small channel fluctuations in both the time and frequency domain over the duration of one Resource Block (RB).
- Synchronous transmission is assumed through the whole area, including desired cells and interference cells.

A resource block is defined as the minimum scheduling unit of the LTE transmission frame structure. In the case of a MBSFN, one subframe contains 12 subcarriers where each subcarrier carries 12 OFDM symbols. One typical edge user is considered with $\mathbf{N}_r$ receiver antennas, knowing that an IRC receiver can suppress up to $\mathbf{N}_r - 1$ interference sources [12] due to the spatial degrees of freedom. The received signal model for such a system can be expressed as:

$$\mathbf{y}(k,l) = \sum_{i=0}^{N_{stm-1}} \sqrt{P_i}\mathbf{H}_i(k,l)\mathbf{s}_i(k,l) + \mathbf{n}_i(k,l) \tag{1}$$

where N_{stm} is the total number of streams, i is the stream index, $i = 0$ represents the desired signal stream and others mean the interference streams. $\mathbf{H}_i(k,l)$ represents the channel matrix between the i-th transmission stream and the receiver. $\mathbf{s}_i(k,l)$ denotes N-dimension streams from the desired transmitter and the interfering transmitter $\mathbf{n}_i(k,l)$ represents the Additive White Gaussian Noise (AWGN) vector ($\mathbf{n}_i(k,l) \sim \mathcal{CN}(\mathbf{0}, \sigma_n^2\mathbf{I})$ where σ_n^2 is the noise variance and $\mathbf{I}$ is the identity matrix). $P_i(k,l)$ is the transmission power of the i-th stream. (k,l) represents the k-th subcarrier of the l-th OFDM symbol. With SFBC, two adjacent subcarriers transmit two information signals. The transmitted block-wise signal is given by:

$$\mathbf{s}_{k,k+1,i} = \begin{bmatrix} s_{1,i}(k) & s_{2,i}(k+1) \\ -s_{2,i}^*(k) & s_{1,i}^*(k+1) \end{bmatrix} \tag{2}$$

where k and $k+1$ represent the two adjacent subcarriers. Following the essential assumptions, the combined received signal of the first subcarrier k and the complex conjugate of the received signal of the adjacent subcarrier k+1 can be expressed as [13]:

$$\begin{bmatrix} y_{1,i}(k) \\ \vdots \\ y_{N_r,i}(k) \\ y_{1,i}^*(k+1) \\ \vdots \\ y_{N_r,i}^*(k+1) \end{bmatrix} = \sum_{i=0}^{N_{stm-1}} \sqrt{P_i} \begin{bmatrix} h_{11,i} & h_{12,i} \\ \vdots & \vdots \\ h_{N_r1,i} & h_{N_r2,i} \\ h_{12,i}^* & -h_{11,i}^* \\ \vdots & \vdots \\ h_{N_r2,i}^* & -h_{N_r1,i}^* \end{bmatrix} \begin{bmatrix} s_{1,i}(k) \\ -s_{2,i}^*(k) \end{bmatrix} + \begin{bmatrix} n_1(k) \\ n_2(k) \\ n_1^*(k+1) \\ n_2^*(k+1) \end{bmatrix} \tag{3}$$

where $(\cdot)^*$ denotes the complex conjugate. Therefore, a vector version of (3) as an extension in the spatial domain of (1) can be expressed as:

$$y(u) = \sum_{i=0}^{N_{stm-1}} \sqrt{P_i}\widetilde{\mathbf{H}}_i(u)\widetilde{\mathbf{s}}_i(k) + \widetilde{\mathbf{n}}_i(u) \tag{4}$$

where $\widetilde{\mathbf{H}}_i(u)$ become a $(2N_r \times 2)$ channel matrix, $\widetilde{\mathbf{n}}_i(u)$ is a $(2N_r \times 1)$ complex noise vector. From (4) we can see the system still remains a single stream transmission from the transmitter's point of view which means using SFBC does not reduce MBSFN transmission efficiency.

B. IRC Weight Matrix and Covariance Matrix Estimation with SFBC

1) SFBC-based IRC weight matrix calculation: If the receiver degree of freedom is larger than the number of interference streams, the IRC receiver can then be used to mitigate the inter-cell interference. Any linear estimator can be formulated as a weight vector. The matrix-wise estimated signal is given by [13]:

$$\widehat{\mathbf{s}}_{\mathbf{i=0}}(\mathbf{k}) = \mathbf{W}^H(u)\mathbf{y}(u) \tag{5}$$

Using MMSE criteria, we minimise the average squared distance between the estimated signal at the receiver and the original signal, given as:

$$\mathbf{W}(u) = \underset{\mathbf{W}(u)}{\arg\min}\, \mathbb{E}\{\|\widehat{\mathbf{s}}_0(k) - \mathbf{s}_0(k)\|^2\} \tag{6}$$

where $\mathbb{E}(\cdot)$ represents the expectation value. Substituting (5) into (6) yields

$$\begin{aligned} \mathbf{W}(u) &= \mathbb{E}\{(\mathbf{W}^H(u)\mathbf{y}(u) - \mathbf{s}_0(k))(\mathbf{W}^H(u)\mathbf{y}(u) - \mathbf{s}_0(k))^H\} \\ &= \mathbb{E}\{\mathbf{W}^H(u)\mathbf{y}(u)\mathbf{y}^H(u)\mathbf{W}(u) - \mathbf{s}_0(k)\mathbf{y}^H(u)\mathbf{W}(u) \\ &- \mathbf{W}^H(u)\mathbf{y}(u)\mathbf{s}_0^H(k) + \mathbf{s}_0(k)\mathbf{s}_0^H(k)\} \end{aligned} \tag{7}$$

Since

$$\mathbb{E}\{\mathbf{y}(u)\mathbf{y}^H(u)\} = \mathbf{R}_{\mathbf{y}(u)\mathbf{y}(u)} \tag{8}$$

$$\mathbb{E}\{\mathbf{s}_0(k)\mathbf{y}^H(u)\} = \mathbf{R}_{\mathbf{s}_0(k)\mathbf{y}(u)} \tag{9}$$

$$\mathbb{E}\{\mathbf{y}(u)\mathbf{s}_0^H(k)\} = \mathbf{R}_{\mathbf{y}(u)\mathbf{s}_0(k)} = \mathbf{R}_{\mathbf{y}(u)\mathbf{s}_0(k)}^H \tag{10}$$

where $\mathbf{R}_{ij}$ represents the covariance matrix of i and j. Therefore:

$$\begin{aligned} \mathbf{W}(u) &= \mathbf{W}^H(u)\mathbf{R}_{\mathbf{y}(u)\mathbf{y}(u)}\mathbf{W}(u) - \mathbf{R}_{\mathbf{s}_0(k)\mathbf{y}(u)}\mathbf{W}(u) \\ &- \mathbf{W}^H(u)\mathbf{R}_{\mathbf{y}(u)\mathbf{s}_0(k)} + \mathbf{R}_{\mathbf{s}_0(k)\mathbf{s}_0(k)} \\ &= \mathbf{W}^H(u)\mathbf{R}_{\mathbf{y}(u)\mathbf{y}(u)}\mathbf{W}(u) - 2\mathbf{R}_{\mathbf{y}(u)\mathbf{s}_0(k)}\mathbf{W}(u) \\ &+ \mathbf{R}_{\mathbf{s}_0(k)\mathbf{s}_0(k)} \end{aligned} \tag{11}$$

Thus, in order to minimise (11) we have to make:

$$\frac{\partial f(\mathbf{W}(u))}{\partial \mathbf{W}(u)} = 0 \tag{12}$$

which leads to

$$\mathbf{R}_{\mathbf{y}(u)\mathbf{y}(u)}\mathbf{W}(u) - \mathbf{R}_{\mathbf{y}(u)\mathbf{s}_0(k)} = 0 \tag{13}$$

Thus,

$$\mathbf{W}(u) = \mathbf{R}_{\mathbf{y}(u)\mathbf{y}(u)}^{-1}\mathbf{R}_{\mathbf{y}(u)\mathbf{s}_0(k)} \tag{14}$$

Since there is no correlation between the desired signal $\mathbf{s}_o$ and the interference signal $\mathbf{s}_{i,i\neq 0}$, as well as with the noise, we have:

$$\begin{aligned} \mathbf{R}_{\mathbf{y}(u)\mathbf{s}_0(k)} &= \mathbb{E}\{(\Sigma\mathbf{H}_i(u)\mathbf{s}_i(k) + \mathbf{n}_i(u))\mathbf{s}_0(k)\} \\ &= \mathbb{E}\{\mathbf{H}_0(u)\mathbf{s}_0(k)\mathbf{s}_0(k)\} \\ &= P_0(k)\mathbf{H}_0(u) \end{aligned} \tag{15}$$

where Σ still sums the same element as (4). With the same principle applied to (8), we obtain:

$$\mathbf{R}_{\mathbf{y}(u)\mathbf{y}(u)} = \mathbb{E}\{P_0(k)\mathbf{H}_0(u)\mathbf{H}_0^H(u) + \sum_{i=1}^{N_{stm-1}} P_i(k)\mathbf{H}_i(u)\mathbf{H}_i^H(u) + \sigma_n^2\mathbf{I}\} \tag{16}$$

Since $P_i(k) = \mathbf{s}_i(k)\mathbf{s}_i^H(k)$, so the second term of (16) becomes:

$$\mathbb{E}\{\sum_{i=1}^{N_{stm-1}} P_i(k)\mathbf{H}_i(u)\mathbf{H}_i^H(u) + \sigma_n^2\mathbf{I}\} = \mathbf{R}_{I+N}(u) \tag{17}$$

which is the interference plus noise covariance matrix. Then (16) becomes:

$$\mathbf{R}_{\mathbf{y}(u)\mathbf{y}(u)} = P_0(k)\mathbf{H}_0(u)\mathbf{H}_0^H(u) + \mathbf{R}_{I+N}(u) \tag{18}$$

Substitute (15) and (18) into (14):

$$\mathbf{W}(u) = (P_0(k)\mathbf{H}_0(u)\mathbf{H}_0^H(u) + \mathbf{R}_{I+N}(u))^{-1}(P_0(k)\mathbf{H}_0(u)) \tag{19}$$

The transmitted signal can THUS be estimated based on (5) as:

$$\widehat{\mathbf{s}}_{\mathbf{0}}(\mathbf{k}) = P_0(k)\mathbf{H}_0^H(u)(P_0(k)\mathbf{H}_0(u)\mathbf{H}_0^H(u) + \mathbf{R}_{I+N}(u))^{-1}\mathbf{y}(u) \tag{20}$$

Apparently, we need to estimate the interference plus noise covariance matrix $\mathbf{R}_{I+N}(u)$.

2) *SFBC interference plus noise covariance matrix calculation:* The CRS-based interference plus noise covariance matrix estimation was investigated in [14] without transmit diversity. This covariance matrix is estimated over one resource block, using the pilot symbols which are known at the receiver which leads to:

$$\mathbf{R}_{I+N} = \frac{1}{M}\sum_{m=1}^{M}[(\mathbf{y}_m(k,l) - \mathbf{H}_{m,0}(k,l)\rho_m(k,l)) (\mathbf{y}_m(k,l) - \mathbf{H}_{m,0}(k,l)\rho_m(k,l))^H] \tag{21}$$

where M is the number of pilots in one RB, and $\rho_m(k,l)$ is the pilot symbol sequence. With SFBC, the covariance matrix extends to the spatial domain according to (17). Here, we set the number of interference sources to be 1 and the receiver dimension equal to 2, due to the size of the covariance matrix:

$$\mathbf{R}_{I+N}(u) = \mathbb{E}\{\Sigma\mathbf{H}_1(u)\mathbf{s}_1\mathbf{s}_1^H\mathbf{H}_1^H(u) + \sigma_n^2\mathbf{I}\} = P_1\begin{bmatrix} |h_{11}|^2+|h_{12}|^2 & h_{11}h_{21}^*+h_{12}h_{22}^* & 0 & h_{11}h_{22}-h_{12}h_{21} \\ h_{21}h_{11}^*+h_{22}h_{12}^* & |h_{21}|^2+|h_{22}|^2 & h_{21}h_{12}-h_{22}h_{11} & 0 \\ 0 & h_{12}^*h_{21}^*-h_{11}^*h_{22}^* & |h_{12}|^2+|h_{11}|^2 & h_{12}^*h_{22}+h_{11}^*h_{21} \\ h_{22}^*h_{11}^*-h_{21}^*h_{12}^* & 0 & h_{22}^*h_{12}+h_{21}^*h_{11} & |h_{22}|^2+|h_{21}|^2 \end{bmatrix} + \sigma_n^2\mathbf{I} \tag{22}$$

In the above matrix, the two diagonal (2×2) dimensional matrices are the covariance matrix of the first subcarriers and the transposed version of the adjacent subcarrier. With the previous assumption, we should have:

$$\mathbf{R}_{I+N}(k) = \mathbf{R}_{I+N}(k+1) \tag{23}$$

Equation (22) becomes

$$\mathbf{R}_{I+N}(u) = \begin{bmatrix} \mathbf{R}_{I+N}(k) & cov(k,k+1) \\ cov(k,k+1)^T & (\mathbf{R}_{I+N}(k))^T \end{bmatrix} \tag{24}$$

where $(\cdot)^T$ denotes the matrix the transpose. In (24), the unknown non-diagonal matrix contains the correlation between the interference transmission channels and the receivers which can both be parameterised as a function of the interference transmitter antenna correlation [13]. Following the simulation results in [13], if we assume the transmitter correlation between the interference source equals to 1, both correlations will become zero. Thus (24) can be approximated to:

$$\mathbf{R}_{I+N}(u) = \begin{bmatrix} \mathbf{R}_{I+N}(k) & 0\mathbf{I}_{N_r} \\ 0\mathbf{I}_{N_r} & (\mathbf{R}_{I+N}(k))^T \end{bmatrix} \tag{25}$$

where $\mathbf{R}_{I+N}(u)$ can be calculated by (21). However, the limited number of samples in one RB may lead to performance degradation for covariance matrix estimation. A well-known solution for this problem is diagonal loading of the covariance matrix. A simple example for diagonal loading of the covariance matrix is to replace the diagonal element matrix of (25) by:

$$\widehat{\mathbf{R}}_{I+N}(k) = \mathbf{R}_{I+N}(k) + \lambda_{DL}\mathbf{I} \tag{26}$$

where λ_{DL} is the diagonal loading factor and $\widehat{\mathbf{R}}_{I+N}(k)$ is the covariance matrix after diagonal loading. Generally, the determination of the diagonal loading factor is scenario dependent, like the method shown in [15] [16], which is not suitable for dynamically changing the wireless communication environment. A scenario independent approach is purposed in [9] and the simulation results show its independence in different LTE interference scenarios. Now, we extend it to a MBSFN interference scenario with the use of SFBC.

C. Covariance Matrix Diagonal Loading Factor Determination

In (21), we have M interference plus noise components to estimate the averaged covariance matrix, and they are independent identical distributed Gaussian vectors. The key concept for the scenario independent diagonal loading is that although the actual covariance matrix is unknown, the likelihood ratio of this covariance matrix is not a function of the actual covariance matrix. The likelihood ratio is given by [17]:

$$LR(\widehat{\mathbf{R}}_{I+N}) = \frac{det(\widehat{\mathbf{R}}_{I+N}^{-1}\mathbf{R}_{I+N})\exp(N_r)}{\exp\left[tr(\widehat{\mathbf{R}}_{I+N}^{-1}\mathbf{R}_{I+N})\right]} \tag{27}$$

where N_r is the number of receiver antennas. It has been proved that the likelihood ratio depends only on the dimension of the receiver plus the degree of accuracy of the covariance matrix estimation [18], i.e. how many pilots are allocated inside one RB. We can pre-calculate the likelihood ratio distribution function with any matrix with a given set of receiver antenna dimensions and pilot numbers, simulating a certain number of trails.

For MBSFN transmission, a resource block will contain 18 pilots, i.e. $M = 18$, and the obtained c.d.f of the likelihood distribution is shown in Fig. 1 for different N_r values. The extracted likelihood ratio median value is given in Table I, corresponding to certain receiver dimensions.

After pre-calculating the median likelihood ratio value, we can find the diagonal loading factor according to:

$$\lambda_{DL} = \arg\min_{\lambda_{DL}} \mathbb{E}\{\|LR(\widehat{\mathbf{R}}_{I+N}(\lambda_{DL})) - \mu(N_r, M)\|^2\} \quad (28)$$

where μ is the likelihood ratio distribution median value. Note that the diagonal loading factor should satisfied $0 < LR(\widehat{\mathbf{R}}_{I+N}(\lambda_{DL})) \leq 1$.

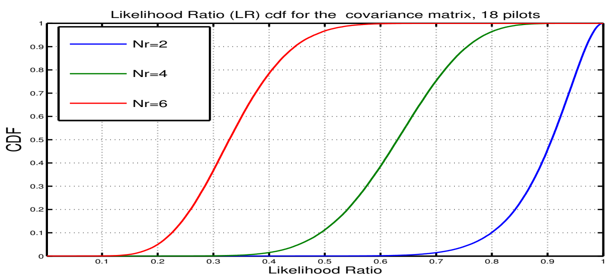

Fig. 1: Likelihood ratio c.d.f for covariance matrix with 18 pilots and $N_r = 2, 4, 6$

TABLE I: Likelihood ratio distribution median value with 18 pilots and $N_r = 2, 4, 6$

N_r	2	4	6
μ	0.907	0.631	0.328

After finding the proper diagonal loading factor value, we substitute it into (26) and finally the SFBC block-wise interference plus noise covariance matrix becomes:

$$\widehat{\mathbf{R}}_{I+N}(u) = \begin{bmatrix} \mathbf{R}_{I+N}(k) + \lambda_{DL}\mathbf{I} & 0\mathbf{I}_{N_r} \\ 0\mathbf{I}_{N_r} & (\mathbf{R}_{I+N}(k) + \lambda_{DL}\mathbf{I})^T \end{bmatrix} \quad (29)$$

Then substitute this diagonal loaded covariance matrix into the IRC weight matrix. The procedure to calculate the SINR in MBSFN and the corresponding achievable spectrum efficiency can be found in [19].

III. Simulation Process

A. Tested Receivers

The receiver schemes are selected in order to investigate:

- The superiority of using SFBC precoding.
- The remains of independence in terms of different SINR values, for the likelihood ratio based IRC receiver in a MBSFN interference scenario.

Systems with and without SFBC precoding are simulated in order to demonstrate the superiority of such precoding schemes in the context of MBSFN. To meet the second objective, an IRC receiver with empirical diagonal loading selection rule is simulated using the method in [16]; the tuned threshold value can be found in [9]. The standard IRC receiver is used in the simulation in order to investigate to what extent the likelihood ratio based approach remains applicable. Additionally, a SFBC-based Maximum Ratio Combining (MRC) receiver using Alamouti coding is added as the baseline to represent the initial condition of all the broadcast users as well as the situation before using the IRC function.

B. Redesigned Pilot Structure

Fig. 2 illustrates the MBSFN transmit frame structure (for one RB) used in the simulation. The fact that the pilot does not employ SFBC means that the pilot-based averaged interference plus noise covariance matrix inversion problem still exists. However, we know that in LTE unicast, orthogonal pilot patterns for different antenna branches can successfully decompose the channel and obtain maximum diversity gain. Thus for the MBSFN pilot pattern, we make pilots orthogonal between different MBSFN transmission antennas. For the two transmitter system under study the number of pilots for each antenna remains as 18RE/RB, keeping the MBSFN standard but half of the positions will be dedicated to transmitting 0s and the rest are normal pilots, vice versa for the second transmit antenna which forms two orthogonal patterns.

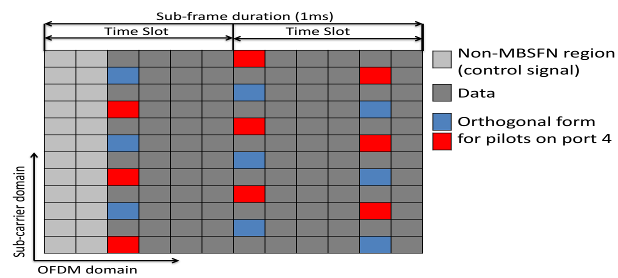

Fig. 2: Redesigned othogonal MBSFN pilot pattern for $2T_x$

In the simulation, we assume the desired signal stream and the interference streams are inside one **big synchronisation area**, where the transmission timing of each subframe is aligned in all cells. The reference signal for interference streams shifts one subcarrier for each interference stream. Therefore, the orthogonal pilot pattern between MBSFN service areas is achieved, the interference reference signal always interferes with the data signals from the serving cell. In order to maintain the fault-resistance of the MBSFN transmission, we have to allocate multiple antennas for each bunch of SFBC code and the antennas that belong to the same group will use the same pilot pattern (basically mixing normal MBSFN and SFBC-MBSFN).

C. Simulation Results

The simulation investigates the MBSFN downlink performance of a single MBSFN multicast user located at the MBSFN area edge, with and without SFBC precoding as well as comparing between the baseline receiver (MRC) and different IRC schemes. The interference sources that affect the desired multicast connection are assumed to be randomly combined adjacent MBSFN services and unicast service that operate on the same frequency at the same time. The simulation parameters are given in Table II.

1) Superiority of SFBC precoding in MBSFN: This set of simulations is to investigate the performance of SFBC precoding in MBSFN compared to one without SFBC coding. In the simulation, a 2x2, single user system is simulated to achieve maximum transmit diversity gain. Single interfering MBSFN transmission is assumed. Simulations are conducted in both noise-limited and interference-limited scenarios (the fixed SIR and SNR value for the two simulation scenes are 0dB and 5dB, respectively.)

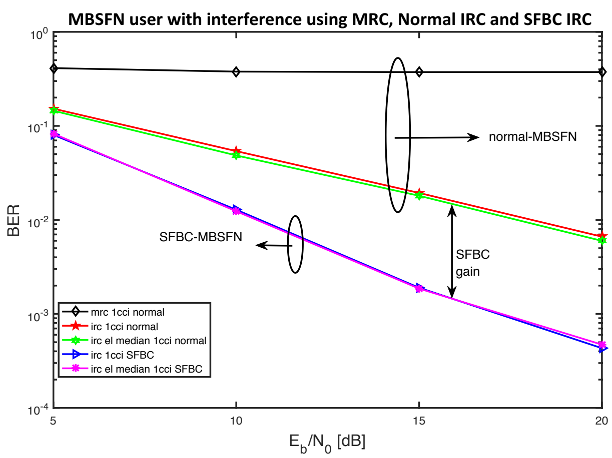

Fig. 3: BER results with fixed SIR, sensitivity case

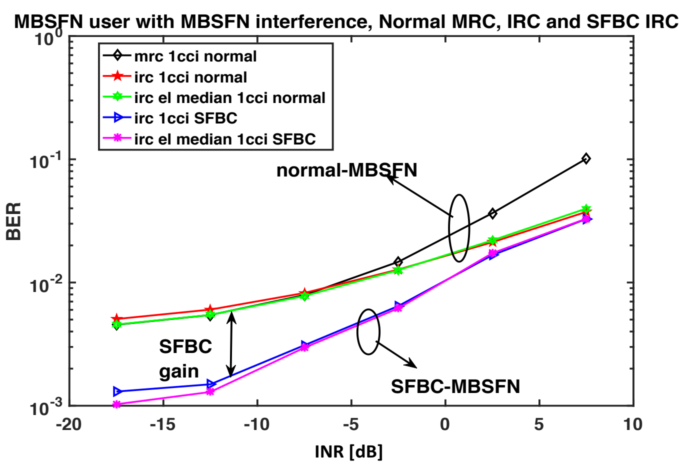

Fig. 4: BER results with fixed SNR, from noise-limited to interference-limited scenario

MRC, standard IRC as well as the diagonal loaded IRC, are simulated with Quadrature Phase Shift Keying (QPSK) modulation. In a sensitivity case, the tested SNR region is between 5 to 20dB with fixed 0dB SIR. For a noise-to-interference limit case, the tested SNR region is between 0 to 25dB with fixed 7.5dB SNR. In Fig. 3, the BER performance of the tested receivers with/without SFBC is shown for a 2x2 system with QPSK. The performance of IRC is similar to IRC with diagonal loading for both with and without SFBC precoding because there is no need for regularisation for a 1 Co-Channel Interference (CCI) system. The SFBC can provide a 3dB SNR gain for a lower SNR region and even better in a high SNR region. On the other hand, the MRC receiver does not take into account interference. Similar observations can be seen from Fig. 4; the performance of the system with SFBC can achieve roughly 10dB gain at the noise-limited region and the gap decreases while going to the high interference limited region. It is expected that the MRC receiver has a better performance in the noise-limited scenario.

2) Performance from Noise-limited to Interference-limited Scenario: The second set of simulations is to investigate the scenario independence performance of MBSFN transmission with SFBC precoding in different interference scenarios, sensitivity and noise-interference limited cases with different parameters in terms of receiver dimensions and the number of interference sources. In the simulation, single user system equipped with two, four or six receiver antennas are tested with different fixed CIR values. Furthermore, the suspendable interference becomes flexible due to the increased spatial degree of freedom. The corresponding simulation scenario parameter is shown on top of each sub-figure in Figs. 5 and 6.

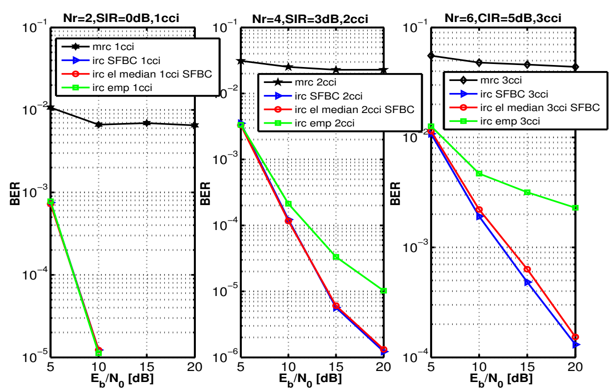

Fig. 5: BER results with fixed SNR, scenario 1

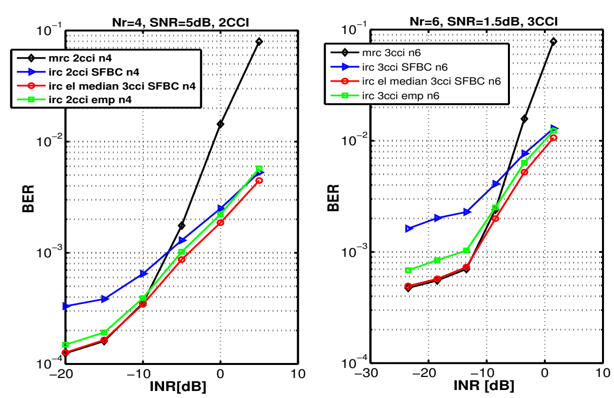

Fig. 6: BER results with fixed SNR, scenario 2

Comparing the likelihood ratio based IRC to the empirical based IRC in Fig. 5, the former has proved its scenario independence in different scenarios. Some performance degradation of the likelihood ratio IRC occurs in three co-channel interference situations; this reflects that in certain degrees of simulation parameter variation, the likelihood ratio based IRC will break down. The second case investigates the four tested receivers at different noise or interference limited environments. As indicated in Fig. 6, the likelihood ratio-based IRC retains its scenario independence regardless of the changes in the simulation environment, without any re-calculation of the diagonal loading factor. One can see that with proper diagonal loading factor selection, the likelihood ratio based IRC can achieve a similar performance with the optimal MRC receiver in the noise-limited scenario and with the standard IRC receiver when in the interference-limited scenario. From all four sets of simulations, one can see that the likelihood ratio based IRC has provided a scenario independent solution for improving the SINR situation for receivers in any environment.

TABLE II: Simulation Parameters

Carrier frequency	2 Ghz
Bandwidth	15.36×10^6Hz
Used/total Sub-carriers	1200/2048
Simulated MBSFN sub-frame	100
Length of Cyclic Prefix (extended)	512
OFDM symbols per subcarrier	12
Sub-carrier per RB	12
Modulation and coding scheme (MCS)	Index=2
Channel model	High performance Radio LAN mode 'e' in [20] outdoor environment with large delay spread
No. T_x	2
No. R_x	2,4,6
No. interference source	1,2,3

IV. Conclusion

In order to increase the spectrum efficiency of the MBSFN service from the receiver side regardless of their location, $i.e.$ different noise or interference level, a scenario independent approach by improving the diagonal loading interference rejection combination has been proposed and investigated in this paper. As verified by the simulation results, such receiver can improve the user SINR situation in a wide range of scenarios. It provides a viable solution to improve the quality of eMBMS services if users are experiencing an SINR value below a certain threshold (to achieve a target SE) without hard switch between MRC and normal IRC at different scenarios and provide a potential solution to support concurrent eMBMS services transmissions. The maximum number of users that can active the IRC function is still under study when considering the trade-off between SE and total receiver computational complexity in a practical case.

Acknowledgment

We would like to acknowledge the support of the University of Surrey 5GIC (www.surrey.ac.uk/5gic) members for this work

References

[1] D. Lecompte and F. Gabin, "Evolved multimedia broadcast/multicast service (embms) in lte-advanced: overview and rel-11 enhancements," *IEEE Communications Magazine*, vol. 50, no. 11, pp. 68–74, November 2012.

[2] "Study on Scenarios and Requirements for Next Generation Access Technologies (Release 14)," 3rd Generation Partnership Project (3GPP), TS 38.913 V14.1.0.

[3] R. Sharma and Y. Cai, "Offline charging for group communications using multimedia broadcast multicast service (mbms) delivery," Apr. 3 2015, uS Patent App. 14/678,858.

[4] "3gpp ts 36.211 channels, physical modulation." *Technical Specification Group Radio Access Network*, 2009.

[5] L. Zhang, Y. Wu, G. K. Walker, W. Li, K. Salehian, and A. Florea, "Improving lte embms with extended ofdm parameters and layered-division-multiplexing," *IEEE Transactions on Broadcasting*, vol. PP, no. 99, pp. 1–16, 2016.

[6] A. Ghosh and R. Ratasuk, "Essentials of lte and lte-a," 2011.

[7] N. Bhushan, J. Li, D. Malladi, R. Gilmore, D. Brenner, A. Damnjanovic, R. T. Sukhavasi, C. Patel, and S. Geirhofer, "Network densification: the dominant theme for wireless evolution into 5g," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 82–89, February 2014.

[8] B. Lindoff, B. Lincoln, and F. Nordström, "Detecting a transmitted ofdm signal in a receiver having at least two receiver branches," Feb. 10 2015, uS Patent 8,953,698. [Online]. Available: http://www.google.ch/patents/US8953698

[9] A. M. Kuzminskiy, Y. I. Abramovich, P. Xiao, and R. Tafazolli, "Uniform expected likelihood solution for interference rejection combining regularization," in *2016 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, March 2016, pp. 3286–3290.

[10] I. Siomina and L. Lindbom, "Reference signal interference management in heterogeneous network deployments," Jul. 16 2013, uS Patent 8,489,029. [Online]. Available: http://www.google.ci/patents/US8489029

[11] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, Oct 1998.

[12] D. A. Wassie, G. Berardinelli, F. M. L. Tavares, T. B. Sorensen, and P. Mogensen, "Experimental verification of interference mitigation techniques for 5g small cells," in *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*, May 2015, pp. 1–5.

[13] Y. Ohwatari, N. Miki, Y. Sagae, and Y. Okumura, "Investigation on advanced receiver employing interference rejection combining for space-frequency block code transmit diversity in lte-advanced downlink," in *2012 IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC)*, Sept 2012, pp. 2414–2420.

[14] Y. Ohwatari, N. Miki, T. Asai, T. Abe, and H. Taoka, "Performance of advanced receiver employing interference rejection combining to suppress inter-cell interference in lte-advanced downlink," in *2011 IEEE Vehicular Technology Conference (VTC Fall)*, Sept 2011, pp. 1–7.

[15] N. Ma and J. T. Goh, "Efficient method to determine diagonal loading value," in *Acoustics, Speech, and Signal Processing, 2003. Proceedings. (ICASSP '03). 2003 IEEE International Conference on*, vol. 5, April 2003, pp. V–341–4 vol.5.

[16] L. Zhang, X. Zhang, and Y. Shen, "Scene detection in interference rejection combining algorithm," in *2012 International Conference on Computer Science and Information Processing (CSIP)*, Aug 2012, pp. 989–992.

[17] Y. I. Abramovich, N. K. Spencer, and A. Y. Gorokhov, "Modified glrt and amf framework for adaptive detectors," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 43, no. 3, pp. 1017–1051, July 2007.

[18] Y. I. Abramovich and B. A. Johnson, "Expected likelihood approach for covariance matrix estimation: Complex angular central gaussian case," in *2012 IEEE 7th Sensor Array and Multichannel Signal Processing Workshop (SAM)*, June 2012, pp. 317–320.

[19] A. Ibrahim, N. Seman, and C. Y. B. Leow, "The investigation of mbms over single frequency network in outdoor urban area," in *2013 IEEE International RF and Microwave Conference (RFM)*, Dec 2013, pp. 125–128.

[20] P. S. Jonas Medbo, "Channel models for hiperlan/2 in different indoor scenarios." Ericsson radio Systemss AB, ETSI EP BRAN, 30 March 1998.